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Review

Use of Real-Time Remote Tele-mentored Ultrasound Echocardiography for Cardiovascular Disease Diagnosis in Adults: A Systematic Review

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ABSTRACT

Cardiovascular diseases remain a major health challenge, leading to high rates of death and hospitalization globally. In the battle against these ailments, echocardiography stands as the frontline tool for diagnosis. Pioneering the charge in innovation, real-time remote tele-mentored ultrasound echocardiography (RTMUS echo) has emerged. This cutting-edge technique facilitates the instant transmission of cardiac imaging from the patient's side to experts in far-off locations, enabling prompt diagnosis and expert consultation. To bridge this gap, a systematic review was conducted to understand RTMUS echo's current applications in diagnosing heart diseases. Searches across six databases, guided by strict inclusion and exclusion criteria, yielded nine relevant articles. These studies assessed the feasibility of RTMUS echo and the technology behind it, confirming its potential for high-quality cardiac imaging. The findings reveal that RTMUS echo could notably improve care for cardiac patients, especially those in resource-constrained settings or in isolation because of infection risks. This technology enables quick access to diagnostic expertise, which is otherwise unavailable in such areas. Future research should aim to optimize the cost-effectiveness and application of RTMUS echo to enhance its benefits for global healthcare.

Introduction

Cardiovascular disease (CVD) has become a leading cause of death and disability worldwide, especially in low- and middle-income countries [1]. It is a significant cause of health disparities and rising healthcare costs in the United States. It was responsible for more than a third of the 2.4 million deaths in the United States in 2003 and the greater than $400 billion spent on healthcare and lost productivity caused by CVD in 2006 [2]. At the beginning of the 20th century, CVD was responsible for less than 10% of all deaths, but by 2001, this figure had risen to 30% [3]. In the United States, heart disease is the primary cause of death, claiming approximately 695,000 lives in 2021, equating to one in every five deaths and incurring an annual cost of about $239.9 billion. Notably, coronary heart disease, responsible for 375,476 deaths in 2021 and affecting around 5% of adults aged ≥20, significantly contributes to cardiovascular mortality and the substantial economic impact through healthcare expenses and lost productivity [4,5]. In high-income countries, nearly 50% of all deaths are due to CVD, whereas in low- and middle-income countries, CVD accounts for around 28% of deaths. Although other causes of death still dominate in certain regions, CVD has become a significant cause of mortality even in those areas [1,3]. A previous study investigated the prevalence and trends in high cardiovascular disease risk among adults in the United States using data from the National Health and Nutrition Examination Survey from 1999 to 2014. The study found that the prevalence of high-risk level did not significantly change over time for the entire sample using the 7.5% 10-y risk level. However, it did decline significantly at a 20% 10-y risk level, and prevalence among non-Hispanic Black males increased dramatically from 53.5% in 1999−2002 to 65.2% in 2011−2014 using the 7.5% 10-y risk cutoff [3]. The demand for evaluating cardiac function and status is significant in hospitals and medical teams because of the high prevalence and severity of cardiovascular disease in patients who require hospital admission.

An echocardiogram is a non-invasive imaging procedure for assessing the heart's function and structures. The major echocardiographic images include scanning protocols such as M-mode, Doppler, color Doppler, 2-D echocardiography and 3-D echocardiography. It produces dynamic images of the heart walls and valves, allowing specialists to assess the blood flow through the heart's chambers and valves [6]. Echocardiography, the primary cardiac examination for suspected cardiovascular complications, requires significant training for accurate performance and interpretation. A well-trained team of expert reviewers and sonographers is crucial, necessitating comprehensive training for aspiring professionals. This training regimen, aligned with established guidelines, emphasizes theoretical education, extensive clinical experience and potential Master's-level courses. Drawing inspiration from the British cardiac physiologist model and the cardiocirculatory physiopathology cardiovascular perfusion technician, this approach highlights the importance of standardized training, accreditation and continuous education to foster the growth of the sonographer profession and address existing barriers in the echocardiography landscape [7].

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In addition, echocardiography specialists may not be available in some situations, such as small clinics, hospitals in rural areas and infectious disease medical teams [2,8,9], to investigate the role of non-invasive cardiovascular imaging in radiology and the percentages of such imaging performed by radiologists and other physicians. The study used the 1998 Medicare Part B database to identify 65 procedure codes related to cardiovascular imaging. It determined the nationwide examination volume, utilization rate and percentage of examinations performed by different physicians. The results revealed that non-invasive cardiovascular imaging is an essential component of radiology practice, with radiologists playing a substantial role in all categories except echocardiography, which cardiologists dominate. The utilization of real-time motion ultrasound (RTMUS) echocardiography has revealed effectiveness in evaluating cardiac function and pathology, encompassing conditions such as cardiac tamponade and right ventricular (RV) strain. Radiologists can concentrate on structural aspects, whereas cardiologists employ advanced assessments, including E-point septal separation for approximating ejection fraction, M-mode and Doppler techniques for valvular pathology and inferior vena cava respiratory variation to gauge fluid responsiveness [10,11]. This highlights the collaborative utility of RTMUS in addressing critical cardiac diagnoses across specialties.

In healthcare, "telemedicine" describes care provided by a physician, whereas "telehealth" refers to care provided by all healthcare professionals, including pharmacists and nurses. The main goal of telemedicine is to use technology to provide clinical support to patients across different geographic locations to improve their health outcomes [12]. This approach helps expand patient care access by removing geographic barriers. The development of telemedicine coincided with the growth of ultrasonography, and one significant advance in the latter was RTMUS, which allows minimally trained sonographers to capture high-quality images with guidance from experts in a different location [13,14]. Tele-echocardiography refers to the use of tele-medicine technology to provide diagnostic imaging information on the heart to healthcare providers regardless of the location of the specialist. It involves the transmission of echocardiogram images using videoconferencing or store and forward transmission of digital imaging data over the Internet. This technology allows patients to receive high-quality cardiac care remotely without traveling to a specialist's location [15,16]. Figure 1 highlights the distinctions between on-site and remote tele-mentored echocardiography workflows. In the on-site scenario, the technician conducts echocardiography and saves and forwards images to cardiologists who interpret results locally. Conversely, in the remote tele-mentored approach, the technician collaborates with an expert who guides the procedure remotely. Real-time image review by experts and remote feedback from cardiologists contribute to a more streamlined diagnostic process.

Tele-echocardiography is a rapidly expanding field, fueled by remarkable technological advancements. Two approaches are available for telemedicine store-and-forward transmission and real-time tele-echocardiography, which have their own limitations. In store-and-forward transmission, medical data, including images and videos, is digitized, compressed, and sent to a remote location for later interpretation. This mode offers flexibility and convenience, allowing asynchronous data exchange, rapid retrieval via the Picture Archiving and Communication System and shared access to data among healthcare professionals. On the other hand, real-time transmission enables immediate and interactive communication, proving valuable in scenarios requiring dynamic assessments, collaborative decision-making and live consultations. The choice between these modes often depends on the nature of the medical scenario, with store-and-forward transmission being suitable for non-emergent situations and real-time transmission being crucial for immediate, dynamic interactions and decision support [6,17].

The adoption of RTMUS is particularly impactful in rural or resource-limited areas, where there is a notable deficit of healthcare specialists. For instance, the study by Meyer et al. [14] documents the effectiveness of RTMUS in trauma care, achieving a 98% success rate for image visualization, despite clinician experience variability [18,19]. This not only showcases the ability of RTMUS to bridge the gap in specialist care but also supports less experienced medical staff. Moreover, research on tele-echocardiography facilitated by nurses with remote cardiologist supervision shows an efficient model, completing the echocardiography workflow within an average of 1.32 ± 0.36 h [20]. This efficiency presents a significant workload reduction potential for cardiologists, particularly vital in rural areas that suffer from a scarcity of primary care physicians [10]. The high accuracy of RTMUS, demonstrated by strong correlation with reference measurements (r = 0.75−0.94 for cardiac indices), further validates

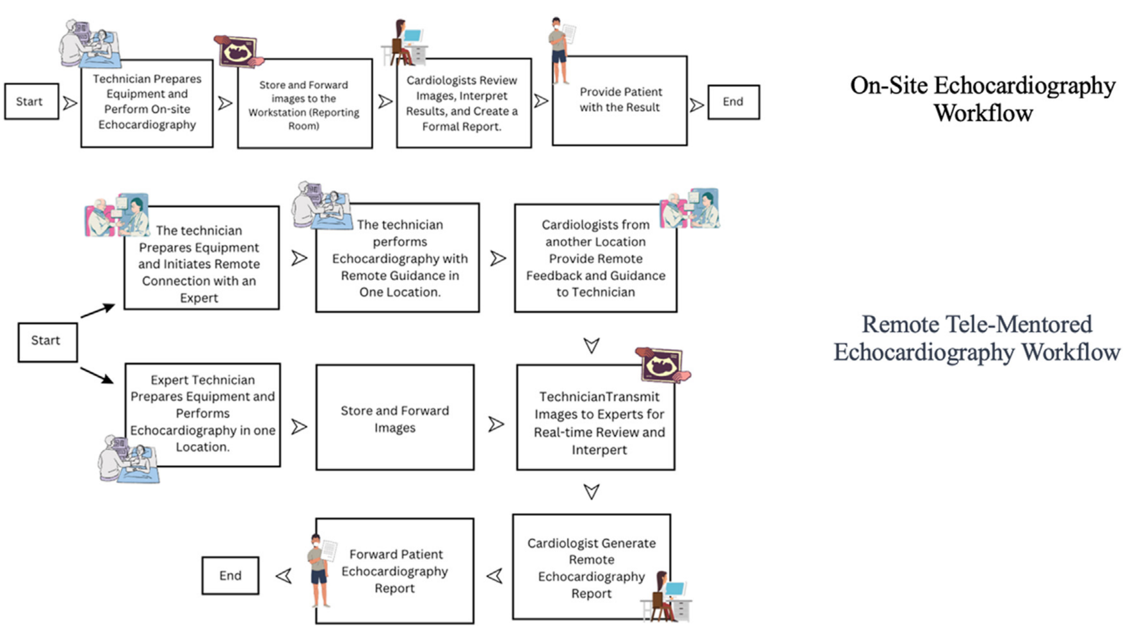

Figure 1. Contrasting on-site and remote tele-mentored echocardiography workflows for enhanced diagnostic processes. This figure highlights the distinctions between on-site and remote tele-mentored echocardiography workflows. In the on-site scenario, a technician conducts the echocardiography procedure, saves the images and forwards them to cardiologists for local interpretation. In contrast, in the remote tele-mentored approach, the technician collaborates with an expert who guides the procedure remotely. Real-time image review by experts and remote feedback from cardiologists contribute to a more streamlined diagnostic process.

its reliability and utility for enhancing healthcare in underserved communities [20]. The innovation of RTMUS echocardiography (RTMUS echo) offers remote expert assistance for bedside clinical evaluations, overcoming challenges of limited specialist access, and is advantageous under strict isolation precautions [15,16]. Therefore, RTMUS stands as a pivotal advancement for remote cardiac care delivery, ensuring quality diagnostics and expanding access to cardiac care in remote regions.

Particularly in the form of real-time tele-mentored echocardiography (RTMUS echo), RTMUS emerges as a telemedicine innovation, enabling remote experts to augment bedside clinical information and surmount the barriers posed by limited specialist access [15,16]. RTMUS is also beneficial in situations requiring strict isolation precautions. Therefore, the adoption of RTMUS can play a crucial role in improving healthcare outcomes and providing high-quality cardiac care remotely for patients in underserved or rural areas. RTMUS effectively addresses critical unmet needs in tele-echocardiography. It resolves challenges in clinical decision-making by empowering minimally trained sonographers to capture high-quality images under remote expert guidance, enhancing diagnostic accuracy and enabling specialized cardiac care delivery in resource-limited or isolated settings [21]. RTMUS significantly optimizes workflow by streamlining the diagnostic process and reducing errors through remote collaboration between on-site technicians and experts. Furthermore, it tackles issues of accessibility to ultrasound services, offering patients in remote or underserved areas high-quality cardiac care without the necessity to travel to a specialist's location [20]. Hence, RTMUS emerges as a potent solution, enhancing clinical decision-making, streamlining workflow efficiency, and improving access to advanced ultrasound services. This, in turn, contributes to a more effective and patient-centric approach in the realm of tele-echocardiography.

Real-time tele-mentored ultrasound echocardiography stands as a vital innovation in remote cardiac care, offering high-quality imaging despite the technical challenges of video signal compression. This modality not only overcomes geographical barriers but also addresses issues of image quality degradation through advanced compression techniques, ensuring that clinicians receive accurate and reliable data for diagnosis [22,23]. An essential approach involves ensuring that RTMUS is conducted with ample bandwidth to facilitate real-time transmission of high-quality images, thereby mitigating the risk of degradation caused by compression. Advanced video compression algorithms play a pivotal role in balancing efficient data transfer while preserving diagnostic clarity. Continuous technological advancements contribute to minimizing compression artifacts, thereby enhancing the overall quality of transmitted echocardiographic images. Standardized protocols for assessing both quantitative and subjective aspects of image quality are crucial, allowing regular evaluations of the imaging system's performance and ensuring prompt identification and resolution of any degradation issues [22,24]. Despite significant progress in overcoming challenges, the frequency of issues related to image quality and compression artifacts varies. Factors such as network conditions, technology infrastructure and user proficiency influence their impact on diagnostic utility. The presence of stable, high-bandwidth networks, sophisticated technology infrastructure and well-trained healthcare professionals collectively contributes to optimizing image quality and minimizing disruptions in diagnostic accuracy [25,26]. These ongoing efforts underscore the efficacy of RTMUS in clinical applications, positioning it as a valuable tool for remote echocardiography with the potential to address challenges associated with image quality and compression artifacts.

Studies in high-income countries have determined the feasibility and accuracy of RTMUS in cardiac, trauma and critical care applications [18,27]. A previous study suggests that this approach could help reduce geographic disparities and provide more patients with the benefits of implementing focused echocardiography by non-cardiologists for diagnostics and follow-up [21].

The need for urgent consultation between out-of-hospital and in-hospital staff is common during resuscitation situations, especially outside regular hours. Verbal communication alone is often insufficient to describe a patient's status, and transmission of radiological images is typically required for optimal management. Although many teleradiology systems have been developed, they are often expensive, not widely available or inconvenient for time-critical cases [28,29]. Despite the growing research on RTMUS echo, there is still a lack of literature regarding its specific usage and the parties involved in its implementation. To address this gap, a systematic review was conducted to provide an overview of the current applications of RTMUS echo in diagnosing and managing cardiovascular dysfunction. The study also aims to propose potential future research based on the findings. The comprehensive overview of the current applications of RTMUS in cardiovascular diagnosis provided by the systematic review can assist policymakers and researchers in identifying potential future uses. The evidence and insights provided by these studies can guide decision-making and direct future research endeavors.

Methods

A comprehensive systematic review was undertaken to explore the utility of RTMUS in evaluating cardiovascular diseases. The reviewers conducted a rigorous search across six prominent databases—MEDLINE, CINAHL, CINAHL Plus, Global Health, Web of Science and PubMed—to identify all relevant studies aligned with the study's objective. Following establishment of the inclusion and exclusion criteria, a preliminary search was carried out using specific keywords. As an example, a total of 97 articles were obtained from the Web of Science by searching for the following keywords: ((((((((ALL = (ramus)) AND ALL = (Real-time remote tele-mentored ultrasound echocardiography)) OR ALL = (Real-time remote tele-mentored echocardiogram)) OR ALL = (tele-Echocardiography)) AND ALL = (remote or telehealth or telemedicine or tele-ultrasound OR tele-echocardiography or tele-mentored)) OR ALL = (Tele Cardiac ultrasound)) OR ALL = (Tele*)) AND ALL = (Cardiac ultrasound)) AND ALL = (echocardiography). Similarly, by use of the keywords (RTMUS or "Real-time remote tele-mentored cardiac ultrasound" or "Real-time remote tele-mentored echocardiography") OR (tele-Echocardiography and (remote or telehealth or telemedicine or tele-ultrasound OR tele-echocardiography or tele-mentored)), a total of 102 articles were obtained from CINAHL Plus with Full Text, CINAHL with Full Text, Global Health and MEDLINE with Full Text. On transmission of the data to Zotero, 36 duplicates were removed, and 66 articles were retained for analysis. Moreover, an additional 106 articles were retrieved from PubMed by searching for articles that matched the following keywords: (((RTMUS) OR (Real-time remote tele-mentored cardiac ultrasound OR Real-time remote tele-mentored echocardiography)) OR (tele-Echocardiography)) AND (remote or telehealth or telemedicine or tele-ultrasound OR tele-echocardiography or tele-mentored). The articles were screened based on pre-defined inclusion and exclusion criteria.

Inclusion criteria comprised (i) articles that were written in English; (ii) studies that focused on real-time tele-echocardiography in adults; and (iii) studies that reported outcomes of tele-echocardiography. Exclusion criteria comprised (i) studies not focused on adults and (ii) studies that were not on real-time tele-echocardiography.

The selected studies underwent rigorous examination to identify their characteristics and outcomes, and pertinent information was extracted accordingly. This information was then entered into a predesigned structured data collection form to facilitate further analysis. Figure 2 is a flowchart of the article selection process following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, including the screening and exclusion criteria used [30]. During the screening process, several articles were excluded because they did not meet the research inclusion criteria. Specifically, 122 articles were excluded because they were review articles, did not report outcomes or were not focused on RTMUS. Additionally, 22 articles that focused on pediatrics were also excluded.

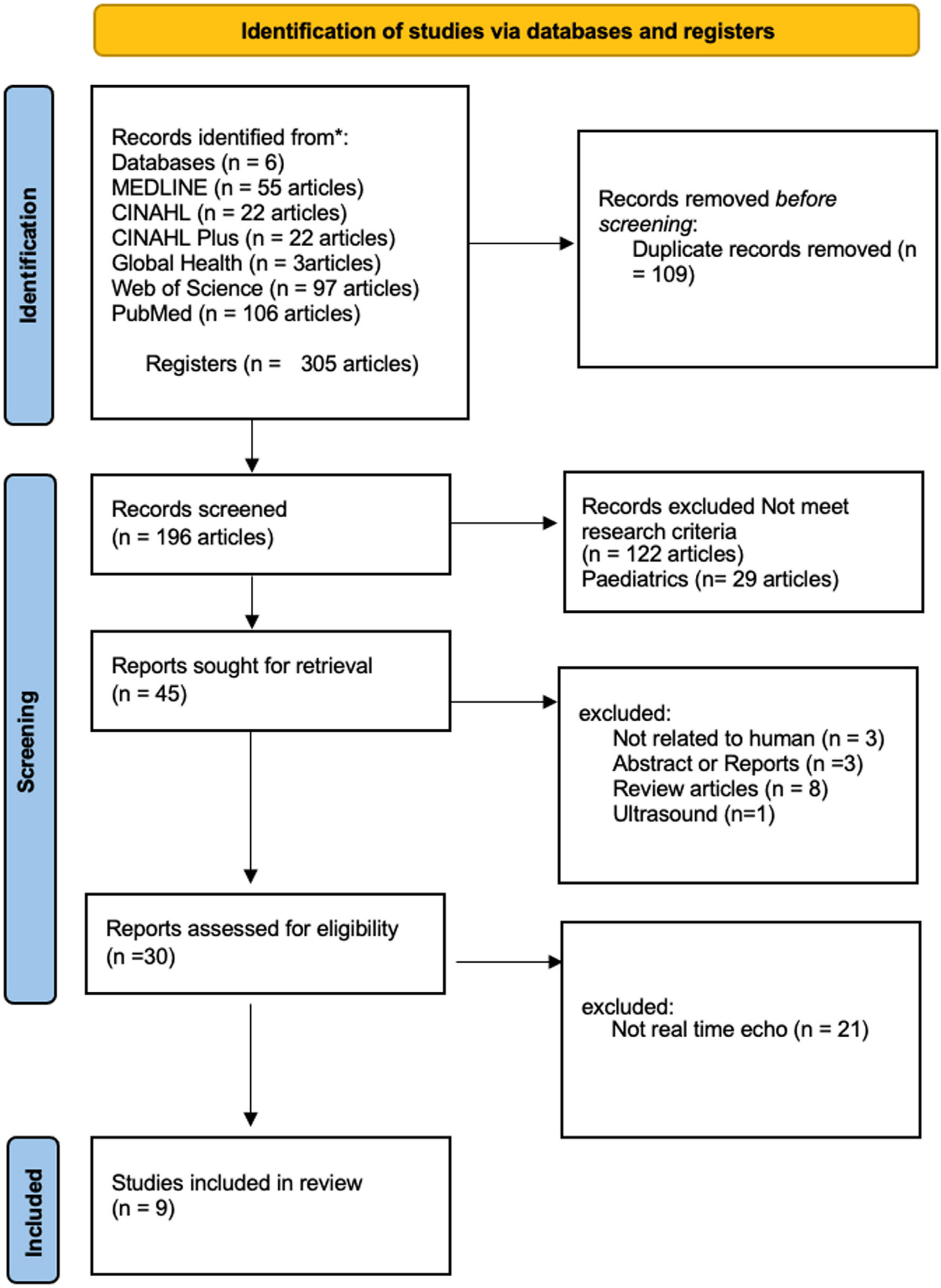

Figure 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for article selection process. This flowchart illustrates the systematic article selection process in accordance with the PRISMA guidelines, including the screening and exclusion criteria used [29]. The process involves multiple stages, such as identification, screening, eligibility assessment and inclusion, leading to the final selection of articles for the study. *Arrows* indicate the flow of the selection process, and decision points are marked based on the specified criteria.

After initial screening, 45 articles were retained for further screening, of which three were unrelated to humans, three were only abstracts or reports, eight were reviews, one focused on general ultrasound and 18 were not conducted in real time. Therefore, these articles were also excluded from the analysis. After the assessment, nine articles were deemed eligible for careful analysis and synthesis and included in the study. The selected articles were presented in two summary tables, each providing an overview of the characteristics of the RTMUS echo studies; because of the heterogeneity of study designs, this review did not conduct a meta-analysis.

Results

In this article, we aim to explore the use of RTMUS tele-echocardiography for evaluating cardiovascular disease in adults. Table 1 provides a concise summary of the essential features of the studies included in the analysis. The selected studies varied significantly with respect to their research questions and the specific utilization of RTMUS echo. The significance of technology in RTMUS echo emerged as a recurring topic of interest in the majority of the studies. The studies employed various ultrasound machines and communication techniques, detailed in Table 2. Articles highlighting potential differences between RTMUS and on-site expert assessments emphasized nuances in interpreting certain findings. For instance, one study [27] noted fair concordance (80%) for lung consolidation, suggesting that conveying subtle aspects of this condition accurately through RTMUS might be challenging. Furthermore, variations in sensitivity for parameters such as right ventricle dilatation/dysfunction and pulmonary interstitial syndrome were observed, implying that the immediate physical presence of an on-site expert could offer additional context and tactile feedback, potentially influencing assessment accuracy.

Feasibility studies constituted the majority of the articles included in the analysis, and two specifically concentrated on the utilization of arm robotics in tele-echocardiography. Various procedures were employed based on the research objectives, and tele-mentors were either emergency physicians or cardiologists. The sonographers involved in the studies encompassed a range of healthcare professionals, including physicians and nurses, as well as non-medically trained individuals who could obtain various cardiac ultrasound views.

Most of the reviewed articles focused on applying RTMUS echo in assessing cardiac function and pathology, including left ventricular and RV function/dysfunction and RV strain. However, a few articles examined limited cardiac images [23,24,31]. Additionally, two articles explored the use of advanced cardiac evaluations with RTMUS echo, including tricuspid annular plane systolic excursion to assess the systolic function of the right ventricle [21,32]. B-mode, M-mode, color Doppler and Doppler flow measurements were used for assessing valvular pathology and the overall heart assessment, employing multiple scanning techniques such as parasternal long and short axis, apical and subxiphoid positions.

Significant variability was observed in the types of experts and learners involved in the reviewed studies, covering aspects such as the time required for image acquisition. For example, the mean duration of focused transthoracic echocardiography was 720 ± 240 s, indicating no statistically significant differences in examination time among three operators, and a slight non-significant reduction in time was noted during the study [32]. Furthermore, variations were noted in the ability to make clinical decisions based on obtained images and the level of agreement between RTMUS echo image findings and other imaging modalities or in-person assessments conducted by expert sonographers. A case in point is the study reporting excellent expert interobserver agreement at 82%, reflected in a Cohen's κ value of 0.82 (95% confidence interval: 0.70−0.94), highlighting the consistency in clinical decision-making among expert observers. Similarly, interobserver agreement, comparing interpretations on workstations and smartphones, demonstrated a high level of 90%, with a Cohen's κ value of 0.86 (95% confidence interval: 0.76−0.97), indicating robust agreement across different technologies and emphasizing the reliability of RTMUS echo image findings in clinical assessments [31]. These findings were consistently reported across multiple studies, as outlined in Table 2. The feasibility of RTMUS intervention has been affirmed as a means to enhance healthcare provision to patients and contribute to patient care. The reviewed studies consistently underscored the pivotal role of technology in tele-echocardiography using RTMUS, with diverse ultrasound machines and communication methods employed throughout the studies.

Discussion

Tele-echocardiography employs telemedicine technology to transmit echocardiogram images over the Internet. This intervention enabled healthcare providers to provide diagnostic imaging information of the heart remotely, eliminating the need for patients having to travel to a specialist's location. This systematic review provides a comprehensive summary of the current utilization of RTMUS for diagnosing cardiovascular dysfunction through tele-echocardiography. It also sought to emphasize the diverse applications of RTMUS while providing some suggestions for potential uses. It delved into diverse scenarios, including feasibility studies in outpatient heart failure clinics, evaluation studies in emergency departments and pilot studies within community-based intensive care units. The research emphasized the versatility of RTMUS, showcasing its adaptability across various healthcare settings. These applications highlighted the technology's potential to enhance diagnostic capabilities and healthcare delivery in different clinical contexts, contributing to a nuanced understanding and providing an overview of its utility.

Like any technological innovation, RTMUS tele-echocardiography demands significant planning before its implementation. Currently, an RTMUS echo program necessitates four essential components: (i) an ultrasound operator to perform images, (ii) an ultrasound machine, (iii) a technological platform enabling active communication between the sonographer and ultrasound expert with simultaneous transmission of ultrasound images and probe location on the patient and (iv) an expert ultrasound consultant for image interpretation [25,26]. The current study found that the implementation of RTMUS varies based on the type of technology used. An example of a simple design in remote telemedicine is a handheld ultrasound device that runs on a tablet. Non-experts can be trained to obtain basic images in real time with guidance from an expert in another location [21]. In contrast, a robotic arm tele-echocardiography system is a more complex RTMUS technology [33,34]. Despite its complexity, this technology holds promise by empowering remote experts to control the imaging process. To facilitate the widespread incorporation of RTMUS, several obstacles must be taken into account. From a clinical perspective, it is crucial to standardize training protocols for ultrasound operators and establish effective communication pathways. On a technical level, addressing the diversity in RTMUS technologies, ranging from handheld devices to robotic systems, requires flexible frameworks and interoperability. Workflow challenges, which involve logistical elements such as training programs, equipment maintenance and seamless integration into existing healthcare processes, demand careful consideration [35]. Overcoming these clinical, technical and workflow challenges is pivotal for the extensive adoption of RTMUS, ensuring its successful integration into various healthcare settings.

Although real-time tele-echocardiography is frequently used, it can potentially result in a degradation of image quality caused by video signal compression. Assessing image quality is crucial for achieving diagnostic accuracy, and a standardized protocol is needed to evaluate both the quantitative and subjective aspects of image quality [25,26]. Furthermore, the impact of Internet connection speed, especially in diverse settings such as mobile networks (3G, 4G, 5G) or WLAN, on image quality caused by data compression is a crucial aspect for RTMUS. The study [32] emphasizes the significance of optimizing image quality based on the specific network conditions. Higher speeds, such as 4G and 5G, may offer advantages in faster data transfer and better resolution, whereas lower-speed networks such as 3G could pose challenges. Advanced video coding standards, such as HEVC and H.264/AVC, help mitigate some issues, but considerations for bandwidth limitations remain [34]. Healthcare providers must balance real-time communication needs with maintaining diagnostic image quality, taking into account varying network conditions in different settings. Ongoing advancements, such as the transition to 5G, may offer improved capabilities for tele-ultrasound, requiring careful adaptation and validation for reliable and high-quality experiences.

Various types of ultrasound equipment were used in the studies presented in this analysis, including Vivid E9, Vivid E95, E-Cube 15 and Vscan (GE Healthcare), which were connected to other modalities where

Table 1
RTMUS echocardiography study characteristic summary table

Article	Study design	Study setting and location	Sample size and characteristics	Data source	Procedure
Hjorth-Hansen et al. 2020 [20]	Feasibility study	Levanger Hospital, Nord −Trøndelag Health Trust Norway	50 outpatients with heart failure who had previous ECG	October 2016 and February 2017 Heart Failure Clinic	Patients were scanned and assessed by one of three expert echocardiographers One of three specialist nurses examined the same patients and transferred the images for interpretation by one cardiologist
Kim et al. 2016 [24]	Feasibility study	Emergency department Korea	100 echocardiographic videos 50 with EF ≥50% and 50 with EF <50%	November 2013 and December 2014 US machine	12 reviewers divided into two groups to review 100 videos alternatively First, 1−50 echocardiographic examinations on an LCD monitor Second, 50−100 on a smartphone
Choi et al. 2011 [31]	Evaluation study	Honduran village Central America	89 patients		Non-expert performed remote ECG using a pocket-size ultrasound device Images and videos were sent to point-of-care diagnosis and reviewed by two experts in the United States workstation All cases re-interpreted on a smartphone
Wejner-Mik et al. 2022 [32]	Feasibility study	Hospital Poland	30 inpatients (18 men and 12 women)		Nurse and two students with no experience in scanning used a PSID to perform the FTTE In real time, a guided cardiologist views and reviews images simultaneously remotely Bedside TTE was performed by an expert for comparison
Kaneko et al. 2022 [21]	Feasibility study	Juntendo University Hospital Japan	31 inpatients with cardiovascular diseases		Trainees scan and interpret the images Trainee re-scans and re-interprets the same patient with tele-ultrasound
Barbier et al. 2012 [23]	Feasibility study	Golgi−Redaelli Institute, rehabilitation unit in the Milan area Italy	95 inpatients	Over a year from January 2008 for patients admitted with cardiovascular or neurological diagnoses	Urgent and routine ECG was performed Videos compressed (stored and forwarded) via the Internet (low bandwidth) in real time or delayed pre-programmed protocol to a notebook PC for a remote cardiologist
Olivieri et al. 2020 [27]	Pilot study	Community-based, university-affiliated ICU department United States	20 patients aged 18 y who had shock or acute respiratory insufficiency	Admitted patient to ICU (April 2017 and August 2017)	Patient examined by both RTMUS and POCUS POCUS = bedside care performed by a fellow who documented the findings Under a remote guideline, the nurse performed an RTMUS examination, and the tele-intensivist documented the findings
Arbeille et al. 2014 [33]	Validation study Robotic arm	University hospital France	41 cardiac patients		Remote sonographers used a motorized probe holder to perform ECG, while a non-sonographer operated the probe positions The sonographer performs a regular ultrasound for 10 min on the same patient
Avgousti et al. 2016 [34]	Experimental evaluation study		2 healthy male participants × 5 videos per participant		Robotic RTMU system where a medical expert remotely operates an ultrasound probe via a robotic interface and a dummy probe for tactile feedback. Video is encoded and then fed to the open-source mHealth expert reviewing on the laptop's monitor employ the same encoding standard for stored ultrasound video on the ultrasound device

ECG, echocardiography; EF, ejection fraction; FTTE, focused transthoracic echocardiography; ICU, intensive care unit; POCUS, point-of-care ultrasound; PSID, pocket-size imaging device; RTMUS, remote tele-mentored ultrasound; TTE, transthoracic echocardiography.

Table 2
RTMUS echocardiography study characteristics summary table

Article	Cardiac US imaging	US machine	Other modalities	Method	Findings
Hjorth-Hansen et al. 2020 [20]	Parasternal (long and short) axis ± color Three apical views ± color LV, LA, RV wave tissue Doppler Pulsed wave and continuous Doppler	Vivid E9 and Vivid E95	EchoPACSWO (version BT12, GE Healthcare)	Evaluation	100% sensitivity and specificity 94% measurement accuracy Acceptable and feasible tool
Kim et al. 2016 [24]	LV systolic function/ parasternal long-axis view	E-Cube 15	iPhone 5S	Evaluation	Viability confirmed for evaluating cardiac function and wall motion No differences in diagnostics between the two displays
Choi et al. 2011 [31]	Parasternal and apical views (long-axis, short-axis and apical four-chamber views)	Vscan (GE Healthcare)	iPhone 3GS with iOS version 4.1	Evaluation	82% agree with the expert readers 61% agree with the interpretation using a smartphone
Wejner-Mik et al. 2022 [32]	Multivariate harmonic imaging and color Doppler No M-mode imaging Parasternal long-axis view Apical: four-, two- and three-chamber view (TAPSE)		Lumify echocardiograph (Philips Healthcare) connected to tablet with a 10.1-inch screen	Evaluation	Sufficient image quality Good correlation of the heart measurement compared with standard echocardiography (LA, LV, AO) Good to very good agreement of detection of abnormalities
Kaneko et al. 2022 [21]	LV, LA measurements (TAPSE) Visual estimation for the LVEF Color Doppler B-mode images		Tablet-based handheld US device (Lumify, Philips)	Evaluation	Feasibility confirmed Perfect agreement between the trainee and a specialist in the evaluation of the valvular disease and LVEF (>50%, 50%−35% or >35%)
Barbier et al. 2012 [23]	Parasternal long- and short-axis Apical four-, five- and two-chamber Apical long-axis Subcostal four-chamber	Sonoline G50 (Siemens AG)	Notebook PC		83% of examinations were clinically useful 100% adequate transmitted images for diagnosis Feasibility confirmed
Olivieri et al. 2020 [27]	B-mode parasternal long- and short-axis subxiphoid positions Visual assessment for LV function and RV dilatation/dysfunction and pericardial effusion	POCUS = SonoSite X-Porte US machine	RTMUS = Philips audiovisual and monitoring software Vidyo audio-video communication solution (Sony EVI-D70 color pan/tilt/ zoom camera)	Evaluation	90%−100% concordance between RTMUS and POCUS (LV function and RV dilatation/dysfunction) RTMUS evaluation accuracy 88%−100% POCUS is a gold standard for RTMUS
Arbeille et al. 2014 [33]	Apical four-/five-chamber views LA and RA LVEF Aortic blood flow velocity Color Doppler/pulsed wave Doppler RV ejection fraction	(Artida, Toshiba Medical, Amsterdam, Netherlands)	Motorized probe holder robotic arm	Evaluation	A reliable diagnosis for 86% and 93% of cases Image quality was lower than that of reference echocardiography 93%−100% of cases had similar measurements
Avgousti et al. 2016 [34]	B-mode, color Doppler, M-mode and pulsed/continuous Doppler		Melody system's robotic arms	Evaluation	High-efficiency video coding can achieve diagnostically lossless video quality within LTE data rates Reliable, remote diagnosis, achieving quality comparable to that of in-hospital US examinations

AO, arota; LA, left atrium; LV, left ventricle; LVEF, left ventricular ejection fraction; POCUS, point-of-care ultrasound; RA, right atrium; RTMUS, remote tele-mentored ultrasound; RV, right ventricle; TAPSE, tricuspid annular plane systolic excursion; TTE, transthoracic echocardiography; US, ultrasound.

the videos and images were compressed and transmitted to experts for interpretation [20,24,31]. The current study found that using a video compression tool and providing effective communication among guided cardiologists, sonographers and non-expert individuals are essential for achieving optimal image quality. Also, effective real-time communication can assist non-experts in obtaining a clear and accurate image, which is crucial for remote cardiologists to interpret and diagnose patients accurately.

In addition, the integration of connection software and/or hardware into echocardiography machines and hospital information technology systems is crucial for the seamless functioning of tele-robotic echography systems. The success of remote echography relies on the efficient transmission of high-quality audio, medical images and haptic feedback between the master station and the slave robot. Dedicated software plays a pivotal role in building a specific telecommunication protocol that prioritizes different flows, such as audio, medical images and haptic control, within a single telecommunication channel. This integration ensures the optimal Visiophonic communication quality, the transmission of high-quality medical images and the real-time feedback required for tele-gesture capabilities [34]. Furthermore, the compatibility with existing hospital information technology systems is essential for the widespread adoption of such tele-robotic echography systems in healthcare centers, facilitating remote consultations and diagnostic procedures while maintaining a balance between quality, bandwidth constraints and cost-effectiveness.

In the context of diagnostic reliability and image quality, a crucial aspect to consider is the involvement of non-experts in performing echocardiograms and the utilization of robotic arms or motorized probe holders. In the study by Arbeille et al. [33], remote sonographers using a motorized probe holder achieved a reliable diagnosis for 86% and 93% of cases, albeit with lower image quality compared with reference echocardiography. On the other hand, Avgousti et al. [34] determined that robotic arms controlled by a remote medical expert using a dummy probe achieved a reliable and remote diagnosis with quality comparable to that of in-hospital ultrasound examinations. The available data suggest that both approaches can yield reliable results, but image quality may vary. Determining the optimal method might depend on specific clinical scenarios, patient populations and the expertise of the remote operator. Implementation and training requirements for each method would likely involve a combination of technical proficiency, familiarity with the robotic systems and adherence to standardized procedures.

In addition, ensuring strict compliance with HIPAA regulations is imperative when securely transferring patient data, particularly within telehealth environments. To uphold the confidentiality and integrity of image data transmission, individuals must adhere to established guidelines, including conducting telehealth appointments in private settings, using personal devices, implementing encryption tools and avoiding exposure to public Wi-Fi networks or USB ports, as elucidated in the provided telehealth privacy and security recommendations [36]. The critical importance of secure data transfer in tele-echocardiography is emphasized in Barbier et al. [23]. A series of meticulous considerations and protocols are instituted to guarantee the confidentiality and integrity of transmitted image data. Initially, the transmission leverages a low-bandwidth Internet connection, with the analog video output undergoing thorough analog-to-digital conversion and compression before transmission. Furthermore, patient clinical information is distinctly transmitted as a text file. In a bid to augment security, the system integrates software password protection and image cropping, systematically eliminating patient-related information. The incorporation of Virtual Private Network (VPN) transmission acts as an additional layer of security, reinforcing the protection of patient data during the transmission process [23]. These measures collectively contribute to upholding the confidentiality and integrity of echocardiographic image data throughout the tele-consultation process. To further fortify the security of tele-echocardiography transmissions, it is advisable to consider implementing robust protocols, including VPN, password protection and image cropping, coupled with ensuring the isolated transmission of patient clinical information in the form of text files.

Evaluation of the intervention RTMUS is crucial for marginalized populations, especially those who are underserved. Equipping these individuals with the necessary skills to locate and assess health information is essential. This need is particularly significant for those living in rural areas facing geographical and other factors common among underserved populations. Furthermore, variations in the implementation of RTMUS tele-echocardiography may also be influenced by available resources, which is a crucial aspect that needs to be taken into consideration. Moreover, the use of robotic arm tele-echocardiography is a promising technology that could be particularly beneficial for isolated patients. Ensuring cost-effectiveness in a program involves matching the appropriate level of technological support, such as US machines and image transmission platforms, with the clinical environment. In resource-limited settings, the quality of images and availability of ultrasonography may necessitate trade-offs, where the focus is on using the most affordable technology capable of answering the clinical question. Therefore, RTMUS has the potential to preferentially benefit marginalized and underserved populations by promoting health information accessibility, adapting to resource constraints and extending specialized services to isolated patients. This approach, underscored by prioritizing cost-effective technological solutions, contributes significantly to addressing healthcare disparities and improving overall health outcomes within underserved communities.

In the realm of real-time tele-echocardiography (RTMUS), the existing literature consists predominantly of small-scale or feasibility studies, particularly within echocardiography. To assess the effectiveness of RTMUS echo in diverse clinical settings, there is a clear imperative for larger-scale research in future endeavors. A strategic shift involves broadening the search criteria to encompass a more varied range of studies on remote ultrasound imaging in different clinical contexts, moving beyond mere feasibility assessments. This shift focuses on larger-scale investigations to firmly establish the efficacy and applicability of RTMUS, not only in cardiology but also in other medical domains. By synthesizing insights from an extensive body of literature, including studies delving into the practicalities and challenges of remote ultrasound imaging in various medical specialties, this research aims to provide a robust foundation for shaping the future trajectory of RTMUS technology.

Most studies included in this paper, however, lack sufficient information on the cost-effectiveness of implementing real-time tele-echocardiography compared with its effectiveness. Therefore, further research is crucial to determine the optimal utilization of RTMUS while considering cost-effectiveness. Future research should also re-examine the trade-off between time, cost and optimal image quality transfer. Finally, identifying the most accessible and user-friendly approaches to implementing RTMUS tele-echocardiography is crucial, potentially involving handheld devices or asynchronous transmission methods that can be easily used by sonographers, patients and remote experts.

Conclusion

This systematic review highlights the potential benefits of RTMUS echo in evaluating cardiovascular diseases in adults. A total of 305 articles were identified from six databases, and nine articles were included in the final analysis based on pre-defined inclusion and exclusion criteria. The selected studies revealed the feasibility and effectiveness of RTMUS in assessing cardiac function and pathology, including left ventricular and RV function/dysfunction, RV strain and valvular pathology. The studies used various procedures and healthcare professionals, including physicians, nurses and non-medically trained individuals. The application of RTMUS in advanced cardiac evaluations, such as tricuspid annular plane systolic excursion, was also explored. Further research is necessary to investigate the full potential of RTMUS in diagnosing and managing cardiovascular diseases in adults, particularly in remote and underserved areas.

Conflict of interest

The author declares no competing interests.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.ultrasmedbio.2024.01.073.

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