Telerobotic Sonography for Remote Diagnostic Imaging

Narrative Review of Current Developments and Clinical Applications

Scott J. Adams, MD , Brent Burbridge, MD, Haron Obaid, MD, Grant Stoneham, MD, Paul Babyn, MDCM, Ivar Mendez, MD, PhD

Access to sonographers and sonologists is limited in many communities around the world. Telerobotic sonography (robotic ultrasound) is a new technology to increase access to sonography, providing sonographers and sonologists the ability to manipulate an ultrasound probe from a distant location and remotely perform ultrasound examinations. This narrative review discusses the development of telerobotic ultrasound systems, clinical studies evaluating the feasibility and diagnostic accuracy of telerobotic sonography, and emerging use of telerobotic sonography in clinical settings. Telerobotic sonography provides an opportunity to provide real-time ultrasound examinations to underserviced rural and remote communities to increase equity in the delivery of diagnostic imaging.

Key Words—robotics; sonography; telehealth; teleradiology; telerobotic; ultrasound

Sonography (ultrasound imaging) is considered a core diagnostic imaging technology and is routinely used to assist in management of a wide variety of diseases across multiple organ systems. Sonography is considered one of the most operator-dependent imaging modalities, and experts are required to provide high-quality diagnostic examinations.[1] There is international variation in those deemed qualified to perform diagnostic sonography; those who perform sonography may include sonographers, radiologists, and, for fetal imaging and echocardiography, obstetricians and cardiologists, respectively, as well as other nonradiologist clinicians.[2] Due to the need for highly trained sonologists or sonographers to perform diagnostic examinations, patients in many rural and remote communities around the world do not have regular access to general sonography, and an even greater number of communities do not have access to subspecialized sonography.[2,3]

Limited access to sonography has motivated efforts to harness advances in robotics and telecommunications to develop telerobotic ultrasound systems: ultrasound systems that allow expert sonographers to manipulate an ultrasound probe in real time from a distant location, thereby allowing sonographers to remotely perform a diagnostic ultrasound examination.[4] After more than 20 years of research and development, the first generation of telerobotic ultrasound systems is now commercially available,[5–7]

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Address correspondence to Scott J. Adams, MD, Department of Medical Imaging, University of Saskatchewan, Royal University Hospital, 103 Hospital Dr, Saskatoon SK S7N 0W8, Canada.

E-mail: scott.adams@usask.ca

Abbreviations
DOF, degree of freedom; FAST, focused assessment with sonography for trauma; ReMeDi, Remote Medical Diagnostician

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promising greater access to sonography for patients in communities that would otherwise not have access to sonography. This narrative review traces the development of telerobotic ultrasound systems and reviews published studies evaluating the feasibility and diagnostic accuracy of telerobotic sonography. The emerging use of telerobotic sonography in clinical settings and opportunities for future research, development, and clinical implementation as telerobotic sonography advances are also discussed.

Literature Search Strategy

The peer-reviewed and gray literature was searched to identify seminal articles on the development of telerobotic ultrasound systems for performing ultrasound examinations at a distance, clinical studies evaluating the feasibility and diagnostic accuracy of telerobotic sonography, and articles describing the use of telerobotic sonography in clinical settings. MEDLINE/PubMed, Google Scholar, Google Search, and the Cumulative Index of Nursing and Allied Health Literature Plus were searched from database inception to April 2020 using a search strategy developed in collaboration with a medical librarian. Search terms included medical subject headings robotics and ultrasonography, as well as combinations of related terms, including echocardiogra*, echogra*, remote operation*, robot*, sonogra*, tele-echocardiogra*, teleechocardiogra*, tele-echogra, teleechogra*, tele-operat*, teleoperat*, tele-robotic*, telerobotic*, tele-sonogra*, telesonogra*, tele-ultraso*, teleultraso*, and ultraso*. Additional search terms included distance, distant, isolated, long-distan*, remote, remote consultation, rural, and rural health services. The search was not restricted by the language of articles. References of articles retrieved were reviewed to identify additional relevant articles. Articles were selected for inclusion in the narrative review if they described technical advancements in the development of telerobotic ultrasound systems for clinical long-distance ultrasound imaging, described the feasibility or diagnostic accuracy of telerobotic sonography in a series of patients, or described the use of telerobotic sonography in clinical settings.

Telerobotic Ultrasound Systems

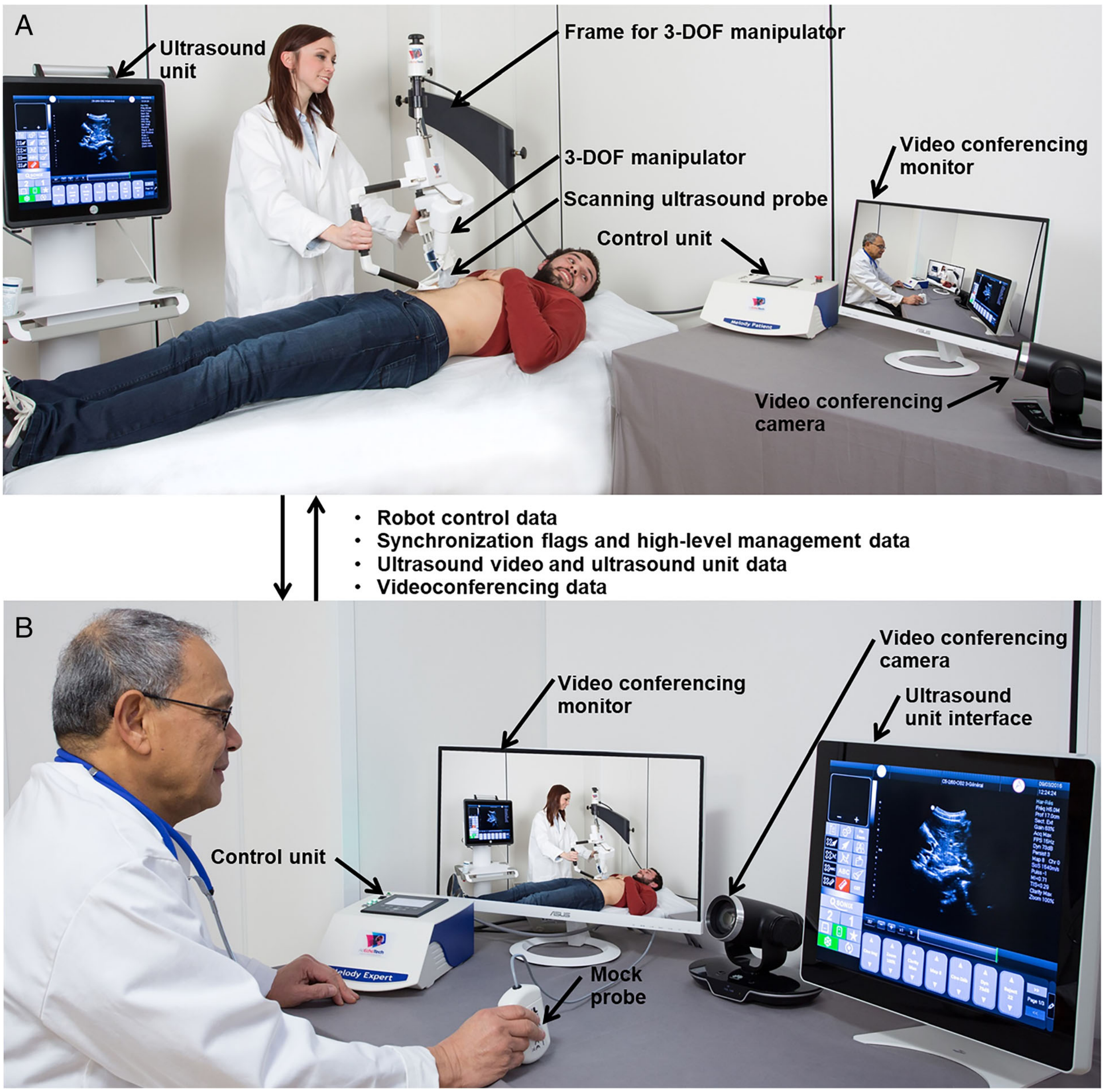
General Concepts

To remotely perform an ultrasound examination, telerobotic ultrasound systems should ideally provide a means for sonographers to remotely manipulate an ultrasound probe, view the ultrasound images on the ultrasound unit interface, remotely control ultrasound unit settings and functions such as gain and depth, and provide a means for the sonographer and patient to communicate. A typical telerobotic ultrasound system is presented in Figure 1. At the patient site, a 3–degree of freedom (DOF) manipulator (robotic arm) holds the scanning ultrasound probe. An assistant at the patient site holds the frame of the 3-DOF manipulator.[4,8] At the sonographer site, the sonographer's movements of a mock probe are directly replicated by the scanning ultrasound probe at the patient site via the 3-DOF manipulator. Through the ultrasound unit interface transmitted to the sonographer site, the sonographer can view all acquired images and control ultrasound unit settings and functions. A standard videoconferencing system provides a means for the sonographer, patient, and patient site assistant to communicate.[4,8]

As telerobotic ultrasound systems are "master–slave" systems, the remote manipulator (end effector) to which the ultrasound probe is attached is controlled by sending position commands from the sonographer site to the patient site.[9] Control of the movements of the end effector is achieved by using various technologies, including a mock ultrasound probe allowing sonographers to use the same movements as when conventionally scanning a patient[4,8] or a computer mouse and graphical user interface to indicate the desired movement or position of the ultrasound probe.[10] An important feature of telerobotic ultrasound systems is the number of DOFs of the robotic manipulator. A greater number of DOFs allows the robotic manipulator to be more dexterous and achieve the basic movements required to replicate ultrasound scanning to a greater extent.[9]

Telerobotic ultrasound systems have been categorized as having applications for short- and long-distance operation.[9] Long-distance telerobotic ultrasound systems enable sonographers to perform ultrasound examinations where substantial geographic distances separate the patient and sonographer: for

Figure 1. A, At the patient site, a 3-DOF manipulator (robotic arm) holds the scanning ultrasound probe. An assistant at the patient site holds the frame of the 3-DOF manipulator and adjusts the frame for the manipulator to control sliding and compression of the probe as instructed by the sonographer. **B**, At the sonographer site, a sonographer or sonologist remotely controls movements of the scanning ultrasound probe (including rocking, rotation, and tilting) by manipulating a mock probe. The sonographer can view all ultrasound images and control ultrasound unit settings and functions through the ultrasound unit interface transmitted to the sonographer site. A standard videoconferencing system provides a means for the sonographer, patient, and patient site assistant to communicate. Data transmitted between the patient site and the sonographer site include robot control data, synchronization flags and high-level management data, ultrasound video and ultrasound unit data, and videoconferencing data.[8] (Images courtesy of Société AdEchoTech; used with permission.)



example, between urban and rural and remote communities. Short-distance telerobotic ultrasound systems enable sonographers to manipulate an ultrasound probe even when they are in the same room as the patient. Potential applications of short-distance telerobotic ultrasound systems—beyond the scope of this review—include integration into robotic surgical systems for image guidance,[11,12] image guidance during robotic brachytherapy seed placement,[12] and robotic positioning of an ultrasound probe when performing an ultrasound-guided procedure.[13]

Telecommunication Requirements

The transmission of data between the patient site and the sonographer site is critical to allow sonographers to remotely control the ultrasound probe and control ultrasound settings and to allow patients and sonographers to communicate with each other. Four types of data flows between the patient site and the sonographer site are generally required to enable telerobotic ultrasound examinations:

1. Robot control data, which are bidirectional data sent to/from the sonographer site to the patient site, enabling movements of the mock probe to be reproduced by the scanning probe at the patient site, and the patient site to the sonographer site, providing haptic feedback;
2. Synchronization flags and high-level management data, which are small bidirectional byte packets used to synchronize the probe manipulator at the patient site and mock probe at the sonographer site, reset the system, and control the sampling frequency for robot control data;
3. Ultrasound video and ultrasound unit data, transmitting ultrasound video from the ultrasound unit located at the patient site to the sonographer site, and control of ultrasound unit settings and functions from the sonographer site back to the patient site; and
4. Videoconferencing data, allowing the patient, sonographer, and patient site assistant to view and communicate with each other.[9]

In telerobotic ultrasound systems, there is an inherent delay in data transmission secondary to the time needed for data to travel over a distance, as well as latency intrinsic to the computer network and communications architecture.[14] The latter is more difficult to predict, as data packets transmitted through a communications network are dynamically allocated according to the network load and routing policies, resulting in latency and jitter (variation).[9,14] Adding to the complexity, congestion may occur if the number of data packets is in excess of the bandwidth that is available, resulting in increased latency.[9]

Ultrasound video data require more bandwidth than robot control data, and the available bandwidth must be shared between these data types. Temporal inconsistency, that is, when different types of data (eg, ultrasound video data and robotic control data) are transmitted at different rates, pose a unique challenge to telerobotic ultrasound systems and multimodal systems in general. Although a delay of 250 milliseconds is not perceivable in terms of isolated visual feedback, a delay of this magnitude is perceived when it represents a delay between commanding an action (such as movement of an ultrasound probe) and receiving visual feedback (such as the resulting ultrasound image).[9,15]

Latency experienced during telerobotic ultrasound examinations is highly variable in published studies, primarily reflecting the available bandwidth. Arbeille et al[16] found a 2-second latency between the instance when ultrasound probe manipulation commands were sent from the sonographer site to when the resulting dynamic ultrasound images were received at the sonographer site. In that study, telerobotic ultrasound examinations were performed at 2 medical centers 50 to 60 km away from the sonographer site at a larger hospital in France, with an available bandwidth of 1 megabits/s and an ultrasound video frame rate of 10 frames/s.[16] In Sweden, Boman et al[17] found that a broadband capacity of 20 megabits/s (with <3% packet loss) was required to ensure a transmission delay of less than 200 milliseconds. Latency was primarily attributable to transfer of videoconferencing data (150 milliseconds) rather than data for controlling the robotic arm (30 milliseconds). In a more recent study, no latency was experienced by the sonographer when using a bandwidth of up to 100 megabits/s between New York and Burlington, Massachusetts, and up to 50 megabits/s between Munich and Boston.[10] The advent of 5G telecommunication technology in the future will substantially increase the data transmission capacity and may resolve the issues of latency.

Table 1. Summary of Preclinical Telerobotic Ultrasound Systems

Reference	Year	Institution of First Author	Country of Development	Name of System	Design	Target Clinical Applications
Pierrot et al[61]	1999	LIRMM	France	Hippocrate	6-DOF jointed arm	Carotid and femoral arteries
Gourdon et al[19]	1999	ENSIB	France	SYRTECH	3-DOF modified wrist	General
Salcudean et al[62]	2000	University of British Columbia	Canada	Not specified	6-DOF parallelogram linkage	Carotid arteries
Masuda et al[63]	2001	Ehime University	Japan	Not specified	6-DOF, 4 jointed legs on rails	Abdomen
Mitsuishi et al[64] and Koizumi et al[65]	2001–2009	University of Tokyo	Japan	Not specified	7-DOF jointed arm	General, including shoulder
Vilchis et al[66] and Banihachemi et al[49]	2003, 2008	TIMC/IMAG Laboratory	France	TER	6-DOF wrist and platform on motor-driven cables	Abdominal and obstetric
Vieyres et al[20]	2003	University of Orleans	France	TERESA	4-DOF spherical wrist and platform	General
Vieyres et al[21]	2006	University of Orleans	France	OTELO	6-DOF wrist and platform	General
Vilchis-Gonzalez et al[67]	2007	Autonomous University of the State of Mexico	Mexico	TERMI	4-DOF rigid arm	Lower limb veins
Solazzi et al[68]	2007	Scuola Superiore Sant'Anna	Italy	EchoDev	5-DOF parallelogram with rotational joints	Peripheral arteries
Janvier et al[69,70]	2008–2014	University of Montreal	Canada	Not specified	6-DOF jointed arm (commercialized F3 articulated robot; CRS Robotics)	Peripheral arteries
Ito et al[71]	2010	Waseda University	Japan	FASTele	4-DOF "wearable" robot	FAST
Carbone et al[72]	2010	University of Cassino	Italy	WTA-1R	6-DOF parallel mechanism	Carotid arteries
Nakadate et al[73]	2010	Waseda University	Japan	WTA-2	3-DOF serial manipulator	Abdomen
Najafi and Sepehri[40]	2011	University of Manitoba	Canada	Not specified	4-DOF wrist	General
Masuda et al[41]	2011	Tokyo University of Agriculture and Technology	Japan	Not specified	6-DOF, 3 jointed legs	General
Nouaille et al[22]	2012	University of Orleans	France	ESTELE	4-DOF serial spherical wrist and platform[a]	General
Nouaille et al[22]	2012	University of Orleans	France	PROSIT	4-DOF wrist and platform	General
Sengupta et al[10]	2014	Icahn School of Medicine at Mount Sinai	United States	Not specified	7-DOF jointed arm[b] (based on the commercialized Cyton gamma configuration servo-actuated robotic arm; Energid Technologies)	Echocardiography and carotid arteries
Monfaredi et al[74]	2015	Children's National Medical Center	United States	Not specified	6-DOF parallel mechanism	General
Seo et al[75–77]	2015–2018	Korea Institute of Machinery and Materials	South Korea	Not specified	6-DOF Stewart platform	General
Pahl and Supriyanto[78]	2015	Ilmenau University of Technology	Germany	Not specified	5-DOF Cartesian coordinate robot	Cervix
Arbeille et al[23]	2016	Unité Médecine Physiologie Spatiale	France	Not specified	DOF not specified; ultrasound probe directly fitted with small internal motors to tilt and rotate the probe ("motorized probe")	General
Mathiassen et al[24]	2016	King's College London	United Kingdom	Not specified	6-DOF jointed arm (based on the commercialized UR5 Universal Robots collaborative robot)	General
Fang et al[25]	2017	Johns Hopkins University	United States	Not specified	6-DOF jointed arm (based on the commercialized UR5 Universal Robots collaborative robot)	General

(Continues)

Table 1. Continued

Reference	Year	Institution of First Author	Country of Development	Name of System	Design	Target Clinical Applications
Sharifi et al[53]	2017	Shiraz University, University of Alberta, and Sharif University of Technology	Iran and Canada	Not specified	Impedance-controlled teleoperation system using a 3-DOF robot (Phantom Premium 1.5A robot; Geomagic) and 2-DOF robot (Quanser) as the master and slave robots, respectively	Imaging of moving anatomic structures, such as the chest or heart
Arent et al[26] and Giuliani et al[28]	2017–2020	Wroclaw University of Science and Technology	Poland	ReMeDi	Integrated robotic system composed of a 7-DOF manipulator for performing ultrasound examinations, a 6-DOF manipulator for palpation, a mobile base, and an integrated videoconferencing system	Echocardiography and abdominal
Lindenroth et al[79]	2019	King's College London	United Kingdom	Not specified	6-DOF soft robotic platform	Obstetric
Wang et al[46]	2019	King's College London	United Kingdom	iFIND	7-DOF Cartesian configuration (version 1) 5-DOF lightweight wrist unit, 2-DOF 2-bar arm-based set of parallel link mechanisms with a 1-DOF rotational axis (version 2) 17-DOF with 2 robotic arms holding and controlling 2 ultrasound probes (version 3)	Obstetric and abdominal
Mathur et al[80]	2019	University of Maryland	United States	Not specified	7-DOF jointed arm (based on a commercialized KUKA collaborative robot)	FAST
Victorova et al[81]	2019	Hong Kong Polytechnic University	China	Not specified	6-DOF jointed arm (based on the commercialized UR3 Universal Robots collaborative robot)	Scoliosis assessment
Huang et al[82]	2019	Northwestern Polytechnical University	China	Not specified	6-DOF jointed arm (based on a commercialized Epson C4 Seiko Epson robotic arm)	Multiple applications with 3-dimensional volume reconstruction
Abbasimoshaii and Najafi[83]	2019	Tarbiat Modares University	Iran	Not specified	Novel cabling mechanism, DOF not specified	Abdominal and pelvic
Sandoval et al[84]	2020	University of Poitiers	France	Not specified	7-DOF jointed arm (based on a commercialized Franka Emika collaborative robot)	General
Tsumura et al[85]	2020	Waseda University	Japan	Not specified	5-DOF, 2 linear stages and 3-axis spring-based passive joints	Obstetric
Zhang et al[86]	2020	Yunnan Open University	China	Not specified	6-DOF jointed arm	Color Doppler, not otherwise specified
Geng et al[87]	2020	Shanghai Jiao Tong University	China	Not specified	6-DOF jointed arm (based on the commercialized UR5 Universal Robots collaborative robot)	General

ENSIB indicates École Nationale Supérieure d'Ingénieurs de Bourges; LIRMM, Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier; and TIMC-IMAG, Techniques de l'Ingénierie Médicale et de la Complexité–Informatique, Mathématiques et Applications, Grenoble.

[a]ESTELE was subsequently commercialized by Robosoft using the same name.

[b]Telerobotic ultrasound system developed by TeleHealthRobotics (Chicago, IL), although currently not commercially available.

Preclinical Telerobotic Ultrasound Systems

Much research in telerobotic sonography has focused on the development of ultrasound probe manipulators to allow sonographers to remotely perform the 5 basic movements of sliding, rocking, tilting, rotating, and compression as required for ultrasound scanning.[18] To achieve at least some of these basic movements, predominant designs in the literature include spherical wrists and jointed arms, with DOFs ranging from 3 to 7. A summary of telerobotic ultrasound systems described in the literature is presented in Table 1.

One of the foremost groups contributing to the development of telerobotic ultrasound systems is the former Vision and Robotics Laboratory, now the PRISME Laboratory, at the University of Orleans in France, which developed a series of telerobotic ultrasound systems that are precursors of the now-commercialized MELODY system (Société AdEchoTech, Naveil, France).[5,19–22] In 1999, Gourdon et al[19] described a telerobotic ultrasound system named SYRTECH, a 3-DOF robot that contacted the patient's body through a ringlike frame. Using a joystick controller, sonographers could remotely control movements of an ultrasound probe.[19] Development was further advanced through support of the European Space Agency and TERESA, OTELO, ESTELE (commercialized by Robosoft, Bidart, France), and PROSIT are telerobotic ultrasound systems emerging from this work, each based on a spherical wrist design.[20–22]

More recently, the size of the probe manipulator was reduced by adding small internal motors to a commercial ultrasound probe.[23] The motorized probe allows sonographers to remotely tilt and rotate the probe, although other movements, including translation, must be made by an assistant based on guidance provided by the sonographer. This design does not include a frame, which is held by the patient site assistant; rather, the patient site assistant directly holds the ultrasound probe.[23] A cohort study comparing motorized probes to a spherical wristlike robotic arm found, on the basis of anecdotal reports, that general practitioners who performed the examinations at the patient site under the guidance of a sonographer thought that the motorized probe system was more ergonomic and easier to use.[23] However, the study did not directly compare the diagnostic performance of each method of scanning in a case-crossover design.

Recent efforts have increasingly explored the use of multipurpose robotic arms to hold an ultrasound probe, with most having a jointed arm design with 6 or 7 DOFs. For example, Mathiassen et al[24] evaluated a 6-DOF collaborative, industrial robot (UR5; Universal Robots, Odense, Denmark) for telerobotic sonography. Requirements for force sensor control, haptic device control, and ultrasound image transfer were defined and achieved with the UR5-based system, although no clinical assessment was performed.[24] The UR5 robotic arm was also used by Fang et al[25] with the goal of creating an ergonomic corobotic system to reduce the amount of force that sonographers must apply when scanning a patient.[25] A group in the United States developed a telerobotic ultrasound system based on a lightweight, commercially available 7-DOF servo-actuated robotic arm (Cyton gamma configuration; Energid Technologies, Cambridge, MA) attached to a customized holder for a standard linear ultrasound probe. Movement of the ultrasound probe was remotely controlled by a computer mouse. A videoconferencing system included 3 cameras at the patient site. Feasibility studies were conducted on a 2-vessel vascular access simulation phantom.[10]

The Remote Medical Diagnostician (ReMeDi) project sought to develop an integrated robotic system enabling physicians to remotely perform assessments, including patient interviews, physical examinations (including observation, auscultation, and palpation), and ultrasound examinations. The system is composed of a 7-DOF manipulator for performing ultrasound examinations, a 6-DOF manipulator for palpation, a mobile base allowing the robot to position beside a patient and move between patients, and an integrated videoconferencing system.[26] Among 12 physicians who assessed the feasibility of the ReMeDi system for abdominal and obstetric ultrasound examinations, all agreed that the system has potential to be introduced into clinical practice. Limitations including synchronizing the orientation of ultrasound probes at the patient site and sonographer site, the loud noise of the robotic arm, and intermittent rapid and unpredictable movements of the robotic arm were identified and subsequently addressed in a second prototype.[27,28]

Commercial Telerobotic Ultrasound Systems

Research and development in the PRISME Laboratory in France led to the commercialization of ESTELE, manufactured by Robosoft, and subsequently MELODY, manufactured by Société AdEchoTech.[5] The MELODY system is a 3-DOF probe manipulator, which, similar to its predecessors, allows the ultrasound probe to contact the patient's body through a ringlike frame that is supported by a floor-mounted stand (Figure 2). In contrast to other systems that used a computer mouse and graphical user interface to control the movements of the manipulator, the MELODY system uses a mock ultrasound probe with sensors to dynamically assess the position of the mock probe and subsequently replicate movements at the patient site. Movements of the scanning ultrasound probe, including rocking, tilting, and rotating, are remotely controlled by manipulating a mock probe at the sonographer site, although an assistant at the patient site controls sliding and compression of the ultrasound probe on the patient's body as instructed by the sonographer.[4,5,8,9] Submission of section 510(k) premarket notification of the intent to market the device was acknowledged by the United States Food and Drug Administration in June 2017, clearing the device for commercial distribution with clinical indications including abdominal, pelvic, urologic, fetal, pediatric, small parts, and peripheral vascular imaging.[6] A medical device license for MELODY was granted by Health Canada in June 2018.[29]

As the robotic manipulator holds an ultrasound probe, the telerobotic system can potentially be used with any ultrasound system. Adams et al[4,8] described the MELODY system integrated with a SonixTablet ultrasound system (BK Ultrasound, Richmond, British Columbia, Canada). All images from the ultrasound unit located at the patient site were also displayed on a monitor at the sonographer site. Settings from the ultrasound unit could be controlled remotely by the sonographer using a touchscreen computer. A videoconferencing system (TE30 All-in-One, HD Videoconferencing Endpoint; Huawei Technologies, Shenzhen, China) between the patient and expert sites allowed the patient, sonographer, and patient site assistant to communicate with each other.[4,8]

A telerobotic ultrasound system specifically for echocardiography, Medirob Tele, was developed by Medirob AB (Skellefteå, Sweden).[7,17] The system consists of a 6-DOF serial robot. In contrast to the MELODY system, which is controlled by a mock probe, Medirob Tele is controlled by a 3-dimensional mouse.[30] Although it is recommended that an assistant be in the room of the patient during examinations, an assistant is not responsible for controlling pressure or gross placement of the robotic arm on the patient's body.[7] A sensor measures the pressure applied on the patient's body and displays the value on the sonographer's monitor.[17] Similar to the MELODY system, the robot can be used with any ultrasound unit; however, full remote control of all ultrasound settings is currently only available with ultrasound units from specific vendors.[7] Although initially developed to perform long-distance imaging in geographic areas in which a sonographer is not available, the Medirob system has also been marketed to reduce musculoskeletal injuries among sonographers.[30]

Most recently, Sensing Future (Coimbra, Portugal), in collaboration with the University of Coimbra, Luz Saúde, and the Instituto Pedro Nunes, adapted a 6-DOF serial robot with haptic feedback to perform abdominal ultrasound examinations as part of the robot sensing for a tele-echography project. The robot is controlled by manipulating a desktop haptic device, which is a miniature version of the 6-DOF robotic arm.[31]

Real-time Remotely Mentored Sonography

Portable, low-cost ultrasound units are rapidly becoming commercially available, including solutions with functionality to allow clinicians to remotely view ultrasound images generated in real time.[32] Although these systems do not allow remote users to control movements of the ultrasound probe or control ultrasound settings, they facilitate real-time remotely mentored sonography to consult with colleagues during scanning.[33] They may also be used in combination with previously discussed probe manipulators as part of a telerobotic ultrasound system.

Philips Healthcare (Amsterdam, the Netherlands) partnered with Innovative Imaging Technologies (Montreal, Quebec, Canada) to integrate Reacts, a secure, collaborative platform with interactive tools for remote virtual guidance, supervision, and training, with its portable ultrasound probe product

Lumify.[32,34] Reacts allows users to collaborate with a colleague through a "tele-ultrasound call" with sharing of ultrasound video and video and audio from a tablet computer.[32] A similar product, Butterfly iQ (Butterfly Network, Guilford, CT), a portable ultrasound probe, allows users to transfer images to and communicate with colleagues via text messaging in real time.[35] Software that prompts users to adjust ultrasound probe positioning to optimize image quality has recently been launched for echocardiography[36] and lung imaging[37] (the latter available for educational use only) as another potential aid for those with less experience with ultrasound scanning.

There is limited evidence regarding the impact of a "remote virtual mentor" on diagnostic accuracy.[38] As sonography is a dynamic modality that requires users to actively identify abnormalities throughout scanning rather than simply document minimum required images, it is anticipated that users must have strong baseline ultrasound skills to effectively use a remote virtual mentor for completion of an entire diagnostic examination if the remote virtual mentor is not able to directly control the ultrasound probe. For certain examinations, however, remote guidance without telerobotic technology may be preferable. Arbeille et al[23] found that remote guidance using an ultrasound system in which experts could remotely control ultrasound settings while a general practitioner performed the examination was preferable to using a robotic arm or motorized probes for interrogation of superficial vessels. The examination type and skills of the assistant or clinician at the patient site will be key considerations in determining an optimal solution for remote sonography. Furthermore, a distinction must be made between point-of-care sonography performed by nonimaging clinicians and diagnostic sonography supervised by radiologists, obstetricians, or cardiologists.[1,39] Point-of-care sonography refers to focused sonographic assessments intended to clarify specific findings, often in an acute or emergent setting, by nonimaging clinicians providing care. Consultative diagnostic sonography refers to ultrasound examinations supervised by consultant imaging specialists after a consultation request, usually from a nonimaging physician. These examinations follow a systematic approach with specific requirements for image archiving, documentation of findings, and communication to referring clinicians.[1] Real-time mentored telesonography may help facilitate the type of focused assessments typical of point-of-care sonography, although it remains unclear what role it may have in facilitating remote diagnostic sonography if the remote virtual mentor is not able to remotely control the ultrasound probe directly.

Clinical Applications

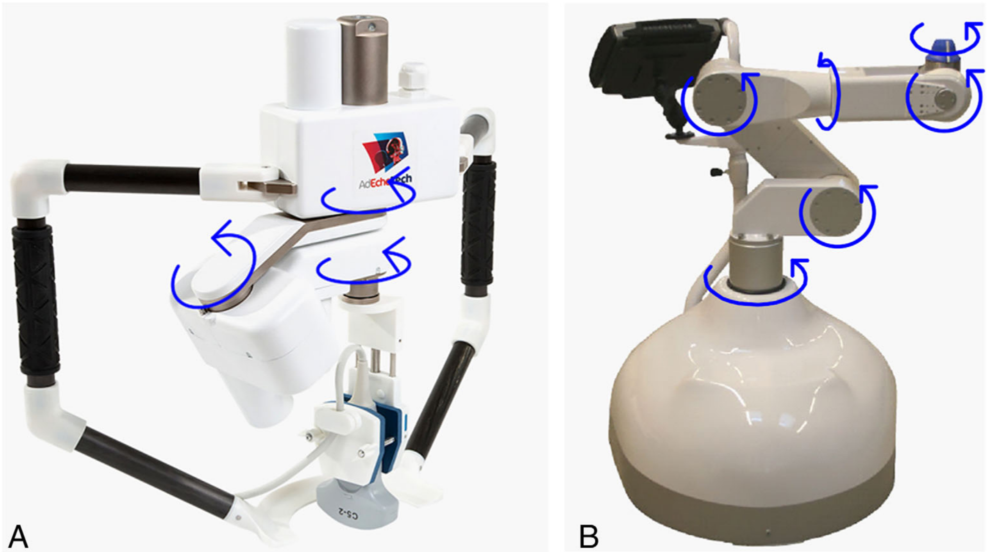
Many studies describing telerobotic ultrasound systems at early stages of technological development have presented limited assessments, demonstrating the utility of the system in imaging a phantom model or performing an ultrasound examination on 1 or a few patients with no robust clinical measures.[40,41] More recently, as telerobotic ultrasound systems have evolved, clinical studies have assessed the feasibility and diagnostic accuracy of telerobotic sonography for abdominal,[4,42–46] obstetric,[8,47] echocardiographic,[42,48] and trauma imaging.[49] These studies have primarily used a case-crossover design with conventional sonography as the reference standard (Table 2). Telerobotic ultrasound systems have also been used to assess the thyroid, leg veins, carotid arteries, and musculoskeletal structures;[16,50] however, these studies were case series with no comparison to a reference standard for assessment of diagnostic accuracy.

Abdominal Imaging

Published clinical studies assessing telerobotic ultrasound systems for abdominal sonography have been conducted in Canada and France. Studies in France have focused on the evaluation of precursors of the MELODY system,[42–45] whereas a study was conducted in Canada investigating the feasibility and clinical performance of the currently commercialized MELODY system.[4] A study evaluating an early-stage telerobotic ultrasound system with limited clinical assessment was also conducted in the United Kingdom.[46]

Arbeille et al[42] assessed an early version of a telerobotic ultrasound system for abdominal and pelvic imaging in 20 patients in a case-crossover study. To simulate remote scanning, patients and the remote sonographer were located in different rooms of the same hospital. Longitudinal and transverse images of the liver (right lobe), gallbladder, portal vein, aorta,

Figure 2. Two robotic arm designs for telerobotic sonography. **A**, Robotic arm of the MELODY patient system, based on a spherical wrist design with 3 DOFs, with demonstrated applications for abdominal and obstetric sonography. **B**, Robotic arm of the Medirob Tele system, a 6-DOF serial robot with demonstrated applications for echocardiography. (Images courtesy of Société AdEchoTech and Medirob AB, respectively; used with permission.)



pancreas, kidneys, bladder, prostate/uterus, and ovaries were successfully acquired in all 20 cases. Satisfactory images of the spleen could not be acquired in 4 of the 20 cases (20%). Results for visualization of important anatomy such as the common bile duct and left lobe of the liver were not reported, and the ability of telerobotic sonography to identify disease was not assessed.[42]

In a subsequent study, Courreges et al[43] compared telerobotic sonography and conventional sonography for abdominal assessments. Of 32 telerobotic examinations, the liver was adequately visualized in 91% of cases, kidneys, spleen, and gallbladder in 85% of cases, and pancreas in 64% of cases. Furthermore, the study assessed the clinical utility of telerobotic sonography for diagnosis: 38 of 57 lesions (66%) detected by conventional sonography were also identified by telerobotic sonography, and of the patients who presented with symptomatic disease, telerobotic examinations enabled a diagnosis in 10 of 12 cases (83%).[43]

Another study, also from France, investigated telerobotic sonography specifically for assessment of the abdominal aorta and common iliac arteries.[44] All 8 abdominal aortic aneurysms (100%) detected by conventional sonography were also detected by telerobotic sonography. The interobserver correlation coefficient for measurement of the aortic diameter was 0.982, and the κ value $\pm$ SD of concordance in evaluating atheromatosis by conventional versus telerobotic sonography was 0.84 ± 0.11.

As a follow-up to their 2003 study, Arbeille et al[45] assessed a precursor of the MELODY system for abdominal sonography, with an additional focus on assessment of disease using the telerobotic ultrasound system. Twenty-six of 35 lesions (74%) identified by conventional scanning were also identified by telerobotic sonography, and at least 1 organ could not be adequately assessed in 11 of 87 telerobotic examinations (13%).

As telerobotic ultrasound systems have advanced to commercialization, Adams et al[4] evaluated the currently commercialized MELODY system for abdominal sonography. As an advancement over previously assessed systems, the MELODY system allowed sonographers or radiologists to control image settings and manipulate the mock probe as if they were controlling a real ultrasound probe. A patient site assistant with no prior experience using ultrasound controlled gross movements of the robotic frame on the patient's abdomen as instructed by the sonographer. Conventional abdominal ultrasound examinations were prospectively performed on 18 patients, followed by a telerobotic ultrasound examination using the MELODY system with a standard ultrasound unit (SonixTablet). Ninety-two percent of all organs included in a standard abdominal sonography protocol were visualized by telerobotic sonography, provided they were also visualized by conventional scanning. Three imaging findings were detected by conventional scanning only; 2 imaging findings were detected by telerobotic scanning only; and 5 imaging findings were detected by both telerobotic and conventional scanning. The fact that lesions not identified by conventional scanning were detected by telerobotic scanning (and did in fact represent true lesions rather than false-positive findings) highlights the operator-dependent nature of sonography and the imperfect nature of using conventional sonography as a reference standard in studies assessing telerobotic sonography. Telerobotic scans took longer than conventional scans (mean duration, 39.9 versus 15.7 minutes), although telerobotic sonography was well received by patients: all patients surveyed indicated their willingness to have a telerobotic examination in the future.[4]

Obstetric Imaging

Similar to abdominal sonography, case-crossover studies assessing telerobotic ultrasound systems for obstetric sonography have been conducted in Canada and France. A study in France evaluated a precursor of the MELODY system,[47] whereas a study in Canada investigated the feasibility and clinical performance of the currently commercialized MELODY system for obstetric sonography.[8]

In a study assessing a precursor of the MELODY system, Arbeille et al[47] found that the fetal presentation, placenta location and echogenicity, and amniotic fluid volume were concordant between all telerobotic and conventional examinations. Biometric parameters measured telerobotically and conventionally were within ±5% in all cases except 2 cases in which the femur length was not measured within the maximum 5-minute time constraint. Scanning of additional anatomic structures was attempted; however, results regarding the ability of the telerobotic ultrasound system to acquire all required images for a complete second-trimester ultrasound examination were not presented.[47]

Adams et al[8] evaluated the MELODY system for both limited and complete obstetric examinations. In a case-crossover study design, limited ultrasound examinations assessing biometry, the placenta location, and amniotic fluid were performed on 20 participants conventionally and telerobotically. Detailed ultrasound examinations, assessing biometry, the placenta location, amniotic fluid, and fetal anatomy, were performed on 10 participants conventionally and telerobotically. For all 4 biometric parameters, intraclass correlations between measurements obtained telerobotically and conventionally were greater than 0.90, indicating excellent agreement. An average of 80% of the 21 anatomic structures attempted in the study protocol were visualized sufficiently by telerobotic scanning, with visualization ranging from 57% to 100% per patient.[8]

Echocardiography

In a 2003 study, Arbeille et al[42] found that a 4-chamber view of the heart was generated in 18 of 20 cases (90%) using an early telerobotic ultrasound system; however, a full echocardiographic assessment was not undertaken. In a subsequent study in 2014 prospectively enrolling 41 patients, Arbeille et al[48] found that 61 of 71 aortic stenoses or valve leaks (86%) identified by conventional sonography were also detected by telerobotic sonography. The left ventricular ejection fraction, aortic flow and right ventricular ejection fraction were measured in 95%, 93%, and 100% of cases, respectively, by telerobotic sonography. No statistically significant difference was identified in most measurements acquired through conventional and telerobotic scanning; however, statistically significant differences in measurements of the aortic blood flow velocity and left ventricular diastolic volume were identified.[48]

Trauma Imaging

In a study assessing a telerobotic ultrasound system for focused assessment with sonography for trauma (FAST), scans were successfully completed with a telerobotic ultrasound system in 10 of 11 patients (90%), eliminating the need for transfer to a different hospital for these 10 patients.[49] However, no findings were detected by telerobotic sonography or

Table 2. Summary of Published Clinical Trials of Telerobotic Sonography

Reference	Year of Publication	Country of First Author	Type of Examinations	Study Design	No. of Patients Enrolled	Primary and Secondary Outcomes
Arbeille et al,[42] preliminary results in Vieyres et al[20]	2003	France	Abdominal, pelvic, cardiac	Case-crossover	20	Liver (right lobe), gallbladder, portal vein, aorta, pancreas, kidneys, bladder, prostate/uterus, and ovaries were visualized telerobotically in 20 of 20 cases (100%). (Visualization of the common bile duct and left lobe of the liver was not reported.) Cardiac 4-chamber view and long-axis views of the spleen were not obtained in 2 of 20 (10%) and 4 of 20 (20%) telerobotic cases, respectively.
Arbeille et al[88]	2004	France	Variable	Case-crossover	105	Complete investigation (visualization) of organs requested for each clinical case was obtained in 80 of 105 telerobotic examinations (76%) compared to 91 of 105 conventional examinations (87%). Duration of telerobotic examinations was 45% higher for telerobotic examinations (16 ± 10 min) than conventional examinations (11 ± 4 minutes).
Courreges et al[43]	2005	France and Spain	Abdominal	Case-crossover	52 (includes 20 patients also reported in Arbeille et al[42] and Vieyres et al[20])	Of 32 telerobotic examinations, the liver was adequately visualized in 91% of cases, kidneys, spleen, and gallbladder in 85% of cases, and pancreas in 64% of cases. 38 of 57 lesions (66%) detected by conventional sonography were also identified by telerobotic sonography. Of the patients who presented with symptoms, telerobotic examinations enabled a diagnosis in 10 of 12 cases (83%). Results of the 20 patients included in Arbeille et al[42] and Vieyres et al[20] are as above.
Arbeille et al,[47] also presented in an abridged form in Arbeille et al[89]	2005	France	Obstetric	Case-crossover	29	Fetal presentation, placenta location and echogenicity, and amniotic fluid volume were concordant between all telerobotic and conventional examinations. Telerobotic and conventional measurements of biometric parameters were within ±5% in all cases, although in 2 cases. Femur length could not be measured within the maximum 5-min time constraint. Results regarding visualization of additional fetal anatomic structures were not presented. Telerobotic examinations were 29% longer than conventional examinations (mean, 18 vs 14 minutes for telerobotic and conventional examinations, respectively).
Martinelli et al,[44] also reported in an abridged form in Banihachemi et al[49]	2007	France	Abdominal aorta and common iliac arteries only	Case-crossover	58	54 of 58 examinations were successfully completed (4 examinations had technical failures). 8 of 8 abdominal aortic aneurysms (100%) detected by conventional sonography were also detected by telerobotic sonography. Interobserver correlation coefficient for measurement of abdominal aortic diameter was 0.982. value of concordance in evaluating atheromatosis using conventional vs telerobotic sonography was 0.84 ± 0.11. Median duration ± SD of telerobotic examinations was 17 ± 8 min compared to 12 ± 7 min for conventional examinations ($P < .001$ based on t test). Global quality evaluation scores were 75.6 ± 15 for telerobotic examinations compared to 87 ± 12.5 for conventional examinations.
Arbeille et al,[45] also presented in an abridged form in Arbeille et al[89]	2007	France	Abdominal	Case-crossover	87	At least 1 organ could not be adequately assessed in 11 of 87 telerobotic examinations (13%). 26 of the 35 lesions (74%) detected by conventional sonography were also detected by telerobotic sonography. Telerobotic examinations were 43% longer than conventional examinations (16 ± 10 compared to 11 ± 4 min).

(Continues)

Table 2. Continued

Reference	Year of Publication	Country of First Author	Type of Examinations	Study Design	No. of Patients Enrolled	Primary and Secondary Outcomes
Banihachemi et al[49]	2008	France	FAST	Case-crossover	11	Telerobotic examinations were successfully performed in 10 of 11 patients (90%). No visceral trauma was detected by telerobotic sonography or conventional sonography in any cases. Telerobotic examinations were 189% longer than conventional examinations (26 compared to 9 min). Transfer to another hospital for a radiologist-performed examination was avoided for 10 of 11 patients (90%). Results for assessment of the abdominal aorta are described in further detail in Martinelli et al.[44]
Arbeille et al[48]	2014	France	Cardiac	Case-crossover	41	61 of 71 valve leaks or aortic stenoses (86%) identified by conventional sonography were also detected by telerobotic sonography. No false-positive results were identified. Left ventricular ejection fraction, aortic flow, and right ventricular ejection fraction were measured in 95%, 93%, and 100% of cases, respectively, by telerobotic sonography. No statistically significant difference was identified in most measurements assessed by conventional vs telerobotic sonography; however, differences in measurements of left ventricle diastolic volume and aortic blood flow velocity were statistically significant.
Boman et al[51]	2014	Sweden and United States	Cardiac	Randomized controlled trial	38	Total process time for cardiology consultation (time from initial examination by a general practitioner until completion of the specialist consultation) decreased from a median of 114 d in the standard-of-care arm to 26.5 d in the arm with telerobotic sonography and teleconsultation ($P < .001$).
Georgescu et al[50]	2016	France	Abdomen, pelvis, lower limb veins, supra-aortic vessels, thyroid, small parts, obstetric	Case series	300	Telerobotic sonography could not be achieved in 10 of 300 cases (3%). Average duration of telerobotic examinations was 24 ± 5 min.
Arbeille et al.[16]	2016	France	Abdomen, pelvis, carotid arteries, lower limb veins, thyroid, MSK, obstetric	Case series	100	97 of 100 (97%) of telerobotic examinations were of sufficient quality for diagnosis. Average duration of telerobotic examinations was 17 ± 4 min.
Arbeille et al[23]	2016	France	Abdomen, pelvis, carotid arteries, thyroid, MSK, obstetric	Cohort study	340	Examinations were performed with a robotic arm (n = 47), motorized probes (n = 92), and nontelerobotic remote guidance (n = 201). Telerobotic examinations provided sufficient information for a safe diagnosis in 329 of 340 examinations (97%). Results were not stratified by method of scanning. Examinations with motorized probes were significantly shorter than with the robotic arm ($P = .012$). Remote guidance examinations in which the expert could modify ultrasound settings were significantly shorter than remote guidance examinations in which the nonexpert adjusted settings ($P = .017$).

(Continues)

Table 2. Continued

Reference	Year of Publication	Country of First Author	Type of Examinations	Study Design	No. of Patients Enrolled	Primary and Secondary Outcomes
Adams et al[4]	2017	Canada	Abdominal	Case-crossover	18	Of organs visualized sufficiently on conventional examinations, 92% were also sufficiently visualized on telerobotic examinations. No statistically significant differences between telerobotic and conventional measurements of the liver, spleen, and proximal aorta were observed; however, telerobotic assessments overestimated or underestimated distal aorta, common bile duct, and kidney measurements. 3 imaging findings were detected by conventional scanning only; 2 imaging findings were detected by telerobotic scanning only; and 5 imaging findings were detected by both telerobotic and conventional scanning. All patients surveyed would be willing to have a telerobotic examination in the future.
Adams et al[8]	2018	Canada	Obstetric	Case-crossover	30 (limited examination: n = 20; detailed examination: n = 10)	Excellent agreement between telerobotic and conventional measurements of all 4 biometric parameters was observed (intraclass correlations >0.90). An average of 80% of the 21 fetal structures attempted in the study protocol were sufficiently visualized by the telerobotic system, with visualization ranging from 57%–100% per patient. 97% of patients surveyed would be willing to have a telerobotic examination in the future.
Wang et al[46]	2019	United Kingdom	Abdominal	Case-crossover	20 (18 included in analysis)	"Good"- or "acceptable"-quality images of the liver, pancreas, and abdominal aorta in 96.6% of images obtained conventionally vs 90.8% of images obtained telerobotically. Images of the gallbladder, spleen, kidneys, and bladder were not reliably obtained by the telerobotic ultrasound system and were not included in the analysis.

MSK indicates musculoskeletal.

conventional sonography in all cases, limiting the ability to draw conclusions regarding the diagnostic accuracy of telerobotic sonography for FAST scans.

Telerobotic Sonography Clinics

Feasibility

Telerobotic sonography provides an opportunity to establish telerobotic sonography clinics in communities that do not have regular access to sonography, enabling patients to receive diagnostic ultrasound examinations in their home community. Case series from France and Sweden have described the types of examinations performed as telerobotic ultrasound systems were deployed in clinical settings.

Arbeille et al[16] performed 100 telerobotic ultrasound examinations using motorized probes in 4 medical centers 50, 60, 1800, and 7000 km from a hospital in France at which a radiologist was based. These included examinations of the abdomen and pelvis (n = 36), vascular structures (n = 42), small parts (n = 22), as well as prenatal examinations (n = 15). They found that 97% of examinations were of sufficient quality for diagnosis, although no comparison to a reference standard was conducted.[16] A French group also evaluated the use of telerobotic sonography at a remote medical center and a seniors' home, each 50 km away from the sonographer site at the hospital. Over a 1-year period, 300 telerobotic examinations were performed, including 68 (23%) abdominal, 20 (7%) pelvic, 138 (46%) carotid artery, 33 (11%) thyroid, 30 (10%) leg vein, and 11 (3.7%) kidney and urinary tract. Telerobotic ultrasound examinations were not successful in 10 of the 300 cases.[50]

Boman et al[51] assessed the feasibility and clinical value of robot-assisted remote echocardiography and teleconsultation for patients with heart failure in a region in northern Sweden. Thirty-eight patients were randomized to either a remote consultation and telerobotic sonography (echocardiography) or the standard of care, which involved patients traveling to the nearest specialist hospital 65 miles away. They found that the total process time for the cardiology consultation (the time from the initial examination by a general practitioner until completion of the specialist consultation) decreased from a median of 114 days in the standard-of-care arm to 26.5 days in the arm with telerobotic sonography ($P < .001$).[51] However, the sustainability of the decreased time to diagnosis in the remote consultation arm over time and with a greater number of patients is unknown.

At the University of Saskatchewan, we are currently conducting a study on the provision of abdominal and obstetric sonography services using the MELODY system to 3 underserviced remote communities located 512, 595, and 1043 km away, respectively, from the location of the sonographer performing the study. We are also developing a telerobotic ultrasound system for musculoskeletal sonography that is suitable for imaging the upper and lower extremities. This may improve access to musculoskeletal sonography for patients who require an assessment of a soft tissue mass in communities that do not otherwise have access to subspecialty musculoskeletal radiology expertise.

Cost Analysis

Little evidence currently exists regarding a cost analysis of telerobotic sonography. A group in northern Sweden assessed costs associated with traditional hospital diagnosis and distance diagnosis (using telerobotic sonography for echocardiography) among patients with heart failure. Costs of the 2 approaches were similar based on the health authority's perspective, although a distance diagnosis approach resulted in reduced costs based on a societal perspective, primarily due to a reduction in travel for patients and patient-related expenses.[52]

Future Directions

Continued advances in robotics and the establishment of 5G telecommunication technology will help advance telerobotic ultrasound systems and help address some of the limitations of current telerobotic ultrasound systems. Increased DOFs to allow the sonographer to control sliding and compression may reduce examination times and improve image quality; a smaller footprint for the frame of the probe holder could help improve visualization of organs for which substantial angulation of the ultrasound probe is required; and modifications to the supporting frame of the probe holder may reduce potential musculoskeletal injury for patient site assistants.[8] Incorporation of haptic technology to telerobotic sonography could provide the expert sonographer additional tactile information while performing the examination. Consideration should also be given to movement of the body surface during breathing, for example, to ensure that the telerobotic ultrasound system complies with the natural movement of the body surface and to ensure that the probe maintains continuous contact with the body surface.[53] The development of telerobotic ultrasound systems for currently unmet needs, such as musculoskeletal sonography, is another opportunity for advancement. The unique anatomy of the upper and lower extremities provides a smaller surface area for scanning than required for abdominal and obstetric scanning, suggesting that dedicated supporting frames and/or manipulators may help meet these needs. There may also be interest in exploring remote vascular sonography, particularly in cases that require urgent or emergent imaging such as in the assessment of possible deep venous thrombosis.

Adaptation of nondedicated commercialized robotic arms for telerobotic sonography may decrease development costs and potentially bring new vendors to the market, although regulatory requirements will be key considerations. Since remote control of ultrasound unit settings and functions is currently available from only specific vendors, the entry of or partnership with major medical imaging vendors will broaden the range of ultrasound units that can be easily used with telerobotic ultrasound systems, potentially improving image quality. Although efforts in telerobotic sonography have primarily focused on solutions that allow sonographers to remotely manipulate an ultrasound probe, development of autonomous ultrasound scanning, which is most established in the area of automated breast sonography,[54] is another area for further advancement. Analyzing force and ultrasound image data together in real time using deep learning, similar to that recently used for vertebral level localization,[55] may be a promising approach toward autonomous ultrasound scanning.

To expand the market for telerobotic ultrasound systems beyond rural and remote communities, developers may wish to consider the potential of telerobotic sonography as an ergonomic solution to reduce musculoskeletal strain among sonographers. Work-related musculoskeletal disorders are particularly prevalent among sonographers, with studies indicating that approximately 90% of sonographers report musculoskeletal pain or discomfort while scanning.[56,57] Injuries can be exacerbated by scanning patients with a high body mass index, as a greater amount of pressure is applied when scanning these patients.[58] Telerobotic systems to reduce the forces that must be applied by sonographers and facilitate more ergonomic positioning while scanning may help reduce musculoskeletal injuries among sonographers.

The commercialization of telerobotic ultrasound systems provides an opportunity for radiology groups to develop telerobotic sonography clinics in underserved communities to expand the reach of their groups, create additional revenue opportunities, provide subspecialty expertise to a greater number of clinics or communities, and bring greater equity to the delivery of ultrasound services. As the cost analysis of telerobotic sonography has been limited to the use of telerobotic technology for echocardiography in Sweden (with no reports indicating cost-effectiveness for general diagnostic sonography), formal cost analyses considering aspects such as equipment costs, staffing needs, examination time, diagnostic performance, and travel costs will be important to support the introduction of this technology into health systems. Additionally, the ability for radiologists and other imagers to bill for studies will be important for broader adoption. The coronavirus 2019 pandemic has helped diminish some of the remuneration barriers for virtual care.[59] This may facilitate the establishment of telerobotic sonography as a viable diagnostic modality. As telerobotic sonography is more widely implemented, it will be critical to identify logistic barriers and solutions for the operation of telerobotic sonography clinics and examine in which contexts telerobotic sonography is found to be an effective means of providing diagnostic sonography.

The ability to provide telerobotic sonography to underserviced populations for whom services are not available may have important applications at a global level, especially in low-resource jurisdictions. The effective use of the limited number of sonographers and sonologists in geographic areas with difficult access to diagnostic services could have a major positive impact. As rapid advancements in remote presence and telecommunication technologies have opened the door to improving access to health care services in remote and rural communities,[60] telerobotic sonography could be a key element in this endeavor. Telerobotic sonography may also be particularly important during epidemics or pandemics, minimizing travel by patients and sonographers to other communities and decreasing transmission of disease between communities. Telerobotic sonography may also allow for increased physical distancing during ultrasound examinations, increasing safety for both patients and sonographers.

Telerobotic ultrasound systems have received regulatory clearance in some jurisdictions, presenting the opportunity for widespread clinical use. However, as radiology groups and health systems consider implementing telerobotic sonography, they should also manage expectations with some of the current limitations of some telerobotic ultrasound systems, including variably longer examination times, the requirement for an assistant at the patient site to assist during examinations, and variable assessments of some required anatomic structures. Results from recent feasibility and diagnostic accuracy studies may inform the types of studies best suited for telerobotic sonography, such as abdominal and limited obstetric scans.[4,8] Additionally, complementary methods, such as nontelerobotic remotely mentored sonography, may be additionally used to ensure that all required anatomy is assessed. New telerobotic ultrasound systems with additional DOFs and haptic feedback continue to be developed; further research is required to determine whether these systems help decrease examination times while improving assessments of anatomic structures.

Conclusions

The technological development of telerobotic ultrasound systems over the past 20 years has led to the commercialization of telerobotic ultrasound systems. This offers an exciting opportunity to implement telerobotic sonography in rural, remote, and low-imaging-volume centers to overcome geographic constraints and provide improved equitable access to sonography. Telerobotic sonography offers several benefits to patients and health systems, including a decreased time to diagnosis, increased access to specialists and subspecialists, a reduced need for travel and transport, cost savings to patients and the health system, and increased reach and revenue for radiology practices. This technology may also have relevance in improving access to sonography services in low-resource countries. For example, focusing on improving access to prenatal sonography in these areas may have a substantial impact on fetal and maternal morbidity and mortality when accompanied by appropriate prenatal care. Further research to develop telerobotic ultrasound systems to meet currently unmet clinical needs such as musculoskeletal sonography and further research to evaluate the health system impact of telerobotic sonography may support the widespread use of telerobotic sonography to overcome geographic constraints and bring greater equity to the delivery of diagnostic imaging.

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