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A Telerobotic Ultrasound Clinic Model of Ultrasound Service Delivery to Improve Access to Imaging in Rural and Remote Communities

SA-CME

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Abstract

Objective: Patients living in many rural and remote areas do not have readily available access to ultrasound services because of a lack of sonographers and radiologists in these communities. The objective of this study was to determine the feasibility of using telerobotic ultrasound to establish a service delivery model to remotely provide access to diagnostic ultrasound in rural and remote communities.

Methods: Telerobotic ultrasound clinics were developed in three remote communities more than 500 km away from our academic medical center. Sonographers remotely performed all ultrasound examinations using telerobotic ultrasound systems, and examinations were subsequently interpreted by radiologists at an academic medical center. Diagnostic performance was assessed by each interpreting radiologist using a standardized reporting form. Patient experience was assessed through quantitative and qualitative analysis of survey responses. Operational challenges and solutions were identified.

Results: Eighty-seven telerobotic ultrasound examinations were remotely performed and included in this study, with the most frequent examination types being abdominal (n = 35), first-trimester obstetrical (n = 26), and second-trimester complete obstetrical (n = 12). Across all examination types, 70% of telerobotic ultrasound examinations were sufficient for diagnosis, minimizing travel or reducing wait times for these patients. Ninety-five percent of patients would be willing to have another telerobotic ultrasound examination in the future. Operational challenges were related to technical infrastructure, human resources, and coordination between clinic sites.

Conclusion: Telerobotic ultrasound can provide access to diagnostic ultrasound services to underserved rural and remote communities without regular ultrasound services, thereby reducing disparities in access to care and improving health equity.

Key Words: Access, rural and remote, telerobotic, telesonography, ultrasound

J Am Coll Radiol 2022;19:162-171.

INTRODUCTION

Access to health care services, including medical imaging, is an important determinant of health [1]. Challenges in accessing health care services can result in delays in diagnosis and treatment, development of advanced disease, and higher rates of complications [2]. Although medical imaging services are widely available in most urban centers, access is limited in many rural and remote communities around the world [3,4]. Availability of ultrasound services in rural and remote communities is

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The authors state that they have no conflict of interest related to the material discussed in this article. Drs. Adams, Babyn, and Mendez are employees. Drs. Burbridge and Chatterson are partners.

1546-1440/21/$36.00 ■ https://doi.org/10.1016/j.jacr.2021.07.023

challenged by difficulty recruiting sonographers to these communities, and because of low volumes of imaging in many smaller communities, it is often unfeasible for radiology practices and health systems to employ sonographers on a full-time or even part-time basis in these communities. Our group's previous research identified many barriers patients in remote communities experience when trying to access ultrasound imaging. For some communities, the closest center with ultrasound services available is hundreds of kilometers away. Family and work responsibilities complicate travel to another community for an ultrasound examination, with patients often having to leave their family behind and find reliable childcare when traveling to another community for an ultrasound examination. In communities that have an itinerant sonographer who periodically visits the community, patients experienced long wait times for an ultrasound examination. In some cases, the many challenges patients faced in accessing ultrasound services led them to choose to not proceed with an ultrasound examination, resulting in a missed opportunity to provide clinically appropriate care [5]. Many rural and remote communities have a large proportion of Indigenous peoples, who experience lower health outcomes relative to non-Indigenous peoples [6]; this makes it even more critical to address disparities among these populations.

Creative solutions to improve access to imaging and improve health equity are critical for radiology practices and health systems to consider. Telerobotic ultrasound is a technology that allows a sonographer or radiologist to remotely manipulate an ultrasound probe and control ultrasound machine settings, allowing sonographers and radiologists to remotely perform an ultrasound examination [7]. In communities in which sonographers are not available on site, telerobotic ultrasound provides an opportunity for sonographers to remotely perform the examination, as well as for radiologists to remotely interpret the examination. This is in contrast to teleradiology, which only allows radiologists to remotely interpret examinations and is reliant on a sonographer physically being present at the same facility as the patient to perform the examination. Prior clinical trials comparing telerobotic ultrasound to conventional ultrasound have demonstrated the feasibility of using telerobotic ultrasound to remotely perform abdominal and obstetrical examinations [8,9]. This technology holds the potential to allow patients to stay in their home community for an ultrasound examination while improving patient access to imaging expertise at larger centers.

The objective of this study was to determine the feasibility of using telerobotic ultrasound to establish a service delivery model to remotely provide ultrasound access to rural and remote communities distributed over a large geographic region. In this article, we describe the development and implementation of telerobotic ultrasound clinics in three northern, remote, Indigenous communities without regular access to ultrasound imaging. To our knowledge, these are the first telerobotic ultrasound clinics in North America. A mixed-methods approach was used to evaluate telerobotic ultrasound as a potential service delivery model to remotely provide ultrasound services, with consideration given to diagnostic assessment, patient experience, and health system and radiology practice integration. Results of this study may inform spread and scale of this ultrasound service delivery model across other radiology practices and health systems to improve access to ultrasound imaging for patients in rural and remote communities and minimize health inequities.

METHODS

Research ethics approval was obtained from the University of Saskatchewan Research Ethics Board.

Setting

Telerobotic ultrasound clinics were established in Stony Rapids, La Loche, and Pelican Narrows, three northern, remote, Indigenous communities in Saskatchewan, Canada, between March 2018 and February 2021. These communities have populations of 262, 2,372, and 1,942 people, respectively, although health centers in these communities also serve neighboring First Nations, increasing their catchment population. None of these communities has a sonographer regularly available on site, but two of these communities, Stony Rapids and La Loche, are served by an itinerant sonographer who visits the communities generally 1 day per month. Any required imaging between these monthly clinics requires patients to travel to another community for imaging. No ultrasound services are available in Pelican Narrows, and all patients must travel to a larger community for imaging. The closest centers that regularly offer ultrasound are approximately 903 km, 507 km, and 121 km away for Stony Rapids, La Loche, and Pelican Narrows, respectively. Each of these communities is subsequently referred to as community A, B, or C (in no particular order) to protect community confidentiality. One of these communities was locked down during the coronavirus disease 2019 (COVID-19) pandemic because of a severe COVID-19 outbreak. During this lockdown, the telerobotic ultrasound service provided diagnostic ultrasound examinations especially for prenatal care. The second community chose to temporarily suspend provision of telerobotic ultrasound services during the early months of the COVID-19 pandemic as part of a suspension of many health care services in their community. The third

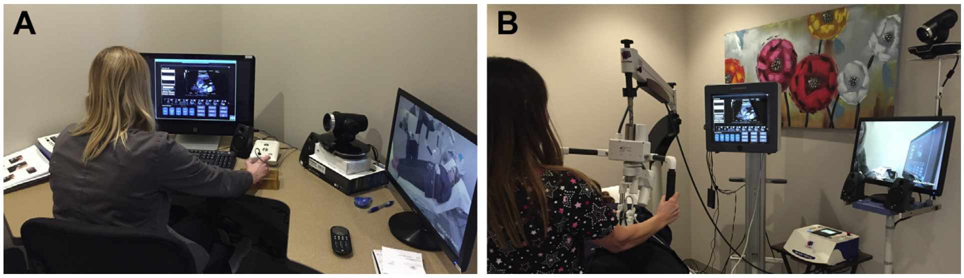

Fig. 1. (A) Sonographer site. The sonographer manipulates a mock ultrasound probe; all movements of the mock probe, including rotating, rocking, and tilting, are replicated by the scanning ultrasound probe at the patient site via a 3-degrees-of-freedom robotic arm. The sonographer can view the ultrasound machine interface, which is transmitted from the patient site and can remotely control all ultrasound machine settings. A videoconferencing system allows the sonographer to communicate with the patient and patient-site assistant. (B) Patient site. The patient-site assistant holds the frame for the 3-degrees-of-freedom robotic arm to which an ultrasound probe is attached. The patient-site assistant ensures sufficient contact between the ultrasound probe and the patient's abdomen and controls translation of the ultrasound probe based on instructions from the sonographer.

community had not yet established a telerobotic ultrasound clinic during the early months of the COVID-19 pandemic.

Clinic Setup

Telerobotic ultrasound systems were transported to and set up at health centers in each of the three communities in collaboration with local clinical leadership. At the remote clinic (patient site), the telerobotic ultrasound system (MELODY system, Société AdEchoTech, Naveil, France) consisted of a control box and a 3-degrees-of-freedom (3-DOF) robotic arm to which an ultrasound probe is attached (Fig. 1). The ultrasound probe was connected to a standard ultrasound machine (SonixTablet, Analogic, Peabody, Massachusetts, in Communities A and B, and TE7 Ultrasound System, Mindray, Shenzhen, China, in community C). A standard video conferencing system (TE30 All-in-One, HD, Videoconferencing Endpoint, Huawei Technologies, Shenzhen, China) and Tixeo Communication Client (Tixeo, Montpellier, France) were used to allow patients, sonographers, and assistants at the patient site to communicate with each other.

A sonographer site was initially established at an imaging clinic associated with our academic radiology group and subsequently at our academic medical center. Driving distances from the sonographer sites to the patient sites were approximately 1,041 km, 592 km, and 509 km for each of the communities, respectively. At the sonographer site, a mock ultrasound probe allowed the sonographer to control rotating, rocking, and tilting of the scanning probe at the patient site via the 3-DOF robotic arm. A computer monitor displayed the ultrasound machine interface, which was transmitted from the patient site via Tixeo Communication Client; this also allowed the sonographer to remotely control the ultrasound machine, including ultrasound unit settings such as gain and depth. A radiologist supervising the examination could also view images in real time using Tixeo Communication Client.

Bandwidth was 20 Mb/s (symmetric), 5 Mb/s (symmetric), and 50 Mb/s (symmetric) in community A, B, and C, respectively. Bandwidth at the sonographer site was 20 to 25 Mb/s (symmetric). This was well above the minimum recommended bandwidth for the telerobotic ultrasound system, which is 100 kb/s for robotic control data, 1 Mb/s (symmetric) for video conferencing data, and 1.5 Mb/s (symmetric) for ultrasound video data.

Assistants were recruited at each of the patient sites to hold the frame for the 3-DOF robotic arm during telerobotic ultrasound examinations, ensure sufficient contact between the ultrasound probe and the patient, and control gross movements of the ultrasound probe (with all fine movements of the ultrasound probe, including rotating, rocking, and tilting, remotely controlled by the sonographer). Patient-site assistants had no prior training in ultrasound, but a 1-hour training session was provided to patient-site assistants before patients were scheduled. This session focused on basic operations of using the telerobotic ultrasound system, including turning on and off each component of the system and establishing and ending a connection with the sonographer site.

Image Acquisition

Participant inclusion criteria for the study were patients referred for an abdominal, pelvic, or obstetrical ultrasound examination by their local physician. Exclusion criteria included patients who did not provide consent to have a telerobotic ultrasound examination and participate in the research study.

A portion of a sonographer's daily schedule was assigned to the telerobotic ultrasound service, with up to four telerobotic ultrasound examinations scheduled on any given day. Sonographers used a telerobotic ultrasound system to remotely perform all ultrasound examinations. Sonographers remotely performed all ultrasound examinations as requested by the referring clinician based on routine imaging protocols for abdominal examinations [10], first-trimester obstetrical examinations [11], second-trimester complete obstetrical examinations [12], pelvic examinations [13], and renal examinations (including assessment of the kidneys and bladder). Limited obstetrical examinations included assessment of fetal anatomy not well assessed on the initial second-trimester fetal anatomic survey, amniotic fluid volume, fetal presentation, and fetal biometry, as requested by the referring clinician. All pelvic and obstetrical examinations were performed transabdominally, and endovaginal scanning was not performed. The duration of each examination (from the times the first and last images were obtained) was recorded.

Sonographers completed a data collection form after each telerobotic ultrasound examination, including a series of Likert items describing their experience communicating with the patient and patient-site assistant, technical challenges encountered during the telerobotic ultrasound examination, and factors limiting diagnostic assessment, including body habitus, bowel gas, fetal lie, gestational age, and telerobotic technology. Patient-site assistants similarly completed a data collection form, which included a series of Likert items regarding their experience during the examination.

Image Assessment

Images from all telerobotic ultrasound examinations were read by one of two board-certified radiologists with 7 and 31 years' experience, respectively, interpreting ultrasound. Images were archived on a provincewide PACS and reported using the same workflow as examinations performed locally. Reports were distributed using existing processes for examinations entered in the provincewide radiology information system. In addition to a standard radiology report, radiologists completed a standardized data collection form to indicate the adequacy of images for diagnosis (adequate, adequate with some reservations, or inadequate), and whether they recommended a follow-up conventional ultrasound to clarify findings on the telerobotic ultrasound examination.

Assessment of Patient Experience

After each ultrasound examination, patients were invited to complete a survey including Likert items based on a previously developed survey [8,9]. Participants were also invited to respond to three open-ended questions: "To you personally, what are the main benefits of having telerobotic ultrasound examinations performed in your community?"; "To you personally, what are the main disadvantages of having telerobotic ultrasound examinations performed in your community?"; and "Please provide any other comments about today's experience having a telerobotic ultrasound examination" [14].

Free-text responses from patient surveys were analyzed using thematic analysis [15]. A standard procedure for thematic analysis was followed based on Braun et al [15]. Two team members familiarized themselves with survey responses, generated initial codes, and generated and revised themes in a reflexive and recursive process [15].

Workflow Challenges and Solutions

Challenges and solutions observed throughout the process of deploying telerobotic ultrasound systems and performing telerobotic ultrasound examinations in the three communities were documented. Consensus on key challenges and solutions was reached by the authors in collaboration with a multidisciplinary team including radiologists, sonographers, IT technicians, clinic coordinators, patient-site assistants, referring clinicians, and health system administrators, as relevant.

Statistical Analysis

Frequencies and proportions were determined for categorical variables, including radiologists' assessment of image adequacy and patients', sonographers', and patient-site assistants' responses to the Likert items on the surveys. Means and SDs (or medians and interquartile ranges) were determined for continuous variables.

RESULTS

Demographic and Examination Information

Seventy-two female and 10 male subjects had telerobotic ultrasound examinations performed across the three communities, including 5 females who had two telerobotic ultrasound examinations performed, both of which are included in this study. Median age (interquartile range) of participants was 30 (22-37) years and 45 (29-60) years for female and male subjects, respectively.

Eighty-seven examinations were performed, including 41 in community A, 36 in community B, and 10 in community C. Examinations performed included abdominal (n = 35), first-trimester obstetrical (n = 26), second-trimester complete obstetrical (n = 12), limited obstetrical (n = 8), pelvic (n = 4), and renal (n = 2) examinations (Table 1). A subset of obstetrical examinations performed in one of the communities was previously reported in an article describing our team's experience deploying a telerobotic ultrasound system during a COVID-19 outbreak [14]. Average (± SD) duration of each telerobotic ultrasound examination was 26

Table 1. Telerobotic ultrasound examinations performed

Type of Examination	n	Average Duration (±SD), Min	Image Adequacy, n (%)			Conventional Examination Recommended, n (%)
			Adequate	Adequate With Some Reservations	Inadequate	
Abdominal	35	26 (±8)	15 (43)	11 (31)	9 (26)	9 (26)
First-trimester obstetrical	26	12 (±7)	16 (62)	5 (19)	5 (19)	5 (19)
Second-trimester obstetrical (complete)	12	35 (±10)	2 (17)	3 (25)	7 (58)	9 (75)
Limited obstetrical	8	17 (±8)	6 (75)	1 (13)	1 (13)	1 (13)
Pelvic	4	11 (±5)	2 (50)	0 (0)	2 (50)	2 (50)
Renal	2	17 (±1)	2 (100)	0 (0)	0 (0)	0 (0)

(±8) min for abdominal examinations, 12 (±7) min for first-trimester obstetrical examinations, 35 (±10) min for second-trimester complete obstetrical examinations.

Latency between movement of the mock probe and resulting change in the ultrasound image was noted by sonographers in 11 (13%) examinations. Sonographers also noted difficulty synchronizing the orientation of the mock probe to the scanning probe in 3 (3%) examinations. Intermittent loss of control of the scanning probe was experienced in 2 (2%) examinations. Although audio quality was sufficient for sonographers and patient-site assistants to communicate with each other for almost all examinations (Table 2), in 5 (6%) examinations sonographers "somewhat disagreed" or "neither agreed nor disagreed" that they were able to effectively communicate with the patient-site assistant regarding probe or patient positioning; these cases were generally those in which a new patient-site assistant without as much experience assisted with the telerobotic ultrasound examinations.

Image Assessment

Across all examination types, radiologists determined 43 (49%) telerobotic ultrasound examinations as adequate for diagnosis, 20 (24%) adequate with some reservations, and 24 (28%) as inadequate for diagnosis (Table 1). Representative images obtained using telerobotic ultrasound systems are provided in Figure 2. The proportion of examinations for which a radiologist subsequently recommended a follow-up conventional ultrasound to clarify findings on the telerobotic ultrasound examination ranged from 0% for renal examinations to 75% for second-trimester complete obstetrical ultrasound examinations (Table 1). Based on the high rate of second-trimester obstetrical ultrasound examinations that were recommended to be repeated as all anatomy could not be adequately assessed, partway through the study it was decided that these examinations would not continue to be performed using the telerobotic ultrasound system.

Among abdominal examinations, assessment was limited because of increased body habitus (n = 18), bowel gas (n = 15), and telerobotic technology (n = 23). Among obstetrical examinations, assessment was limited because of body habitus (n = 14), fetal lie (n = 13), gestational age (n = 12), and telerobotic technology (n = 29). Among pelvic examinations, assessment was limited because of increased body habitus (n = 1), bowel gas (n = 1), and telerobotic technology (n = 2).

Patient Experience

Ninety-five percent of patients indicated they would be willing to have another telerobotic ultrasound examination in the future (Table 2). Four themes were identified regarding patients' experiences during telerobotic ultrasound examinations:

1. Appreciation for having ultrasound available closer to home, which eliminated the need to travel, minimized travel costs, and provided increased convenience
2. Increased ultrasound availability, including decreased wait times for examinations, faster time to diagnosis, and the potential for telerobotic ultrasound to be available for emergencies (another viewpoint was that the telerobotic ultrasound service was not sufficiently available to meet community needs)
3. Novelty of the technology, with one participant describing the experience as "weird" and another commenting that it "didn't seem real" in comparison with their prior experiences having ultrasound examinations
4. Increased safety during the COVID-19 pandemic, because the technology allowed patients to stay in their own community and receive care from health care providers from their own community, minimizing spread of severe acute respiratory syndrome coronavirus 2

Table 2. Patient and provider experiences during telerobotic ultrasound examinations

	Strongly Agree, n (%)	Somewhat Agree, n (%)	Neither Agree nor Disagree, n (%)	Somewhat Disagree, n (%)	Strongly Disagree, n (%)
Patients					
1. I would be willing to have another telerobotic ultrasound examination if I required another ultrasound examination in the future.	29 (69)	11 (26)	0 (0)	1 (2)	1 (2)
2. I felt comfortable communicating with the remote sonographer using the video conferencing system.	34 (81)	7 (17)	1 (2)	0 (0)	0 (0)
3. I felt comfortable knowing that a person in a different room was controlling the ultrasound probe.	34 (81)	7 (17)	0 (0)	1 (2)	0 (0)
4. Having telerobotic ultrasound imaging available in my own community is important.	32 (76)	8 (19)	1 (2)	1 (2)	0 (0)
Sonographers					
1. The audio was of sufficient quality to allow me to adequately communicate with the patient-site assistant.	73 (87)	9 (11)	0 (0)	1 (1)	1 (1)
2. There was no significant lag time between movement of the probe at the expert site and image response.	55 (65)	22 (26)	2 (2)	3 (4)	2 (2)
3. The patient-site assistant and I were able to effectively communicate regarding probe or patient positioning.	63 (75)	15 (18)	1 (1)	5 (6)	0 (0)
Patient-site assistant					
1. The audio was of sufficient quality to allow me to adequately communicate with the remote sonographer.	32 (94)	0 (0)	0 (0)	2 (6)	0 (0)
2. The sonographer and I were able to effectively communicate regarding probe or patient positioning.	33 (97)	1 (3)	0 (0)	0 (0)	0 (0)

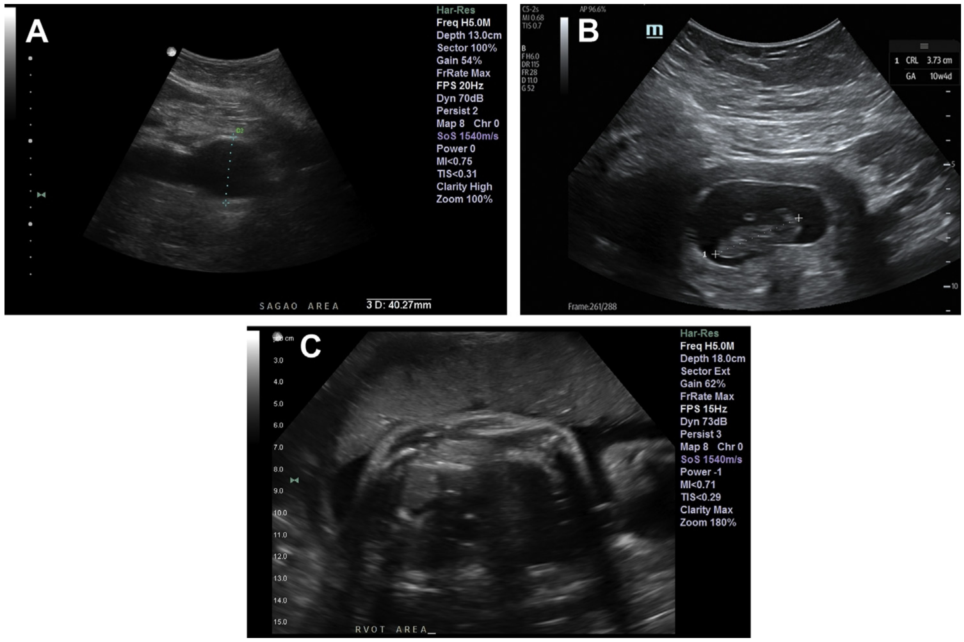

Fig. 2. Representative images obtained using telerobotic ultrasound systems. (A) A 76-year-old man referred for follow-up of an abdominal aortic aneurysm. Sagittal ultrasound image of the abdominal aorta demonstrates stability of the 4.0-cm abdominal aortic aneurysm. (B) A 23-year-old woman referred for a first-trimester obstetrical ultrasound for pregnancy dating. Ultrasound demonstrates a single viable intrauterine gestation with a crown-rump length of 3.7 cm, corresponding to an estimated gestational age of 10 weeks 4 days, and a fetal heart rate of 145 beats per minute (not shown in figure). (C) A 34-year-old woman referred for a second-trimester complete obstetrical examination. The examination was limited because of maternal body habitus and difficulty remotely manipulating the ultrasound probe. Fetal cardiac structures, including the right ventricular outflow tract (attempt shown in figure), were inadequately assessed, and a recommendation was made for a repeat examination.

Workflow Challenges and Solutions

Challenges and solutions from our experience developing three telerobotic ultrasound clinics in northern, remote, Indigenous communities are summarized in Table 3. Operational challenges were related to technical infrastructure, human resources, and coordination between clinic sites.

DISCUSSION

This study describes the development and evaluation of three telerobotic ultrasound clinics in northern, remote, Indigenous communities and investigates the feasibility of this service delivery model to remotely provide ultrasound access to rural and remote communities. The majority of telerobotic ultrasound examinations performed successfully answered clinical questions, minimizing the need for patients to travel to another community for imaging or wait for an itinerant sonographer to visit the community. Patients identified multiple benefits of telerobotic ultrasound, most notably reduced travel, and most patients felt that having telerobotic ultrasound imaging available in their own community was important to them.

Minimizing geographic barriers to ultrasound services is a key step toward better health equity. Our previous work investigating access to ultrasound in northern, remote, Indigenous communities found that geographic remoteness was a central barrier for patients [5]. Other factors, including work and family responsibilities, were exacerbated by geographic remoteness, because an ultrasound appointment that might otherwise take 2 hours for a patient residing in a city might take 2 days or more for a patient living in a remote community who must travel long distances to an ultrasound facility [5]. Minimizing distance from ultrasound services is critical to ensure equitable access. Telerobotic ultrasound clinics may be an important step toward reducing disparities in access to care and health outcomes between urban and rural or remote populations. Indeed, one of the main themes that emerged from patients' experiences in our study is that telerobotic ultrasound reduced the need for travel. Telerobotic technology may be particularly important for urgent or emergent ultrasound examinations. Although at this point we have not developed an after-hours (on-call) telerobotic ultrasound service, in the future this may be considered to better serve rural and remote communities. In

Table 3. Operational challenges and solutions in the development and implementation of telerobotic ultrasound clinics

Challenges	Solutions
Technical infrastructure	
Navigating institutional policies regarding deployment and integration into RIS and PACS	Involve senior health system leadership early to help facilitate integration of telerobotic technology into existing workflows and infrastructure.
Setup of the telerobotic ultrasound system and ongoing maintenance and troubleshooting	Ensure IT technicians are dedicated to the project and have sufficient time to address IT issues as they arise, with backup coverage available if one technician is away. Develop a strong working relationship with the vendor to troubleshoot any issues that arise.
Lag time (robotic control and ultrasound images)	Ensure sufficient bandwidth at both the sonographer site and patient site and ensure IT technicians consider existing firewalls at both sites.
Human resources	
Availability of sonographers	Ensure that sufficient sonographer capacity is available before launching a new site to ensure telerobotic ultrasound is a reliable, regularly available service.
Availability of radiologists	Ensure a specific radiologist is assigned to cover all telerobotic ultrasound examinations on a given day. Integrate telerobotic ultrasound as a modality in the radiology practice's shared scheduling system.
Coordination between sites	
Communication between remote communities and sonographer site	Ensure a coordinator is available to serve as a liaison between radiologists, sonographers, and staff in the remote communities.
Appropriateness of ultrasound examination requisitions	Clearly define the types of examinations which can be facilitated using the telerobotic ultrasound system. For example, practices may wish to specify that pelvic and second-trimester obstetrical examinations should not be performed telerobotically. Ensure a lead sonographer screens examination requisitions before they are scheduled to help ensure all examinations are successfully completed.

RIS = radiology information system.

addition, the value of telerobotic ultrasound for remote communities was highlighted during the current COVID-19 pandemic. A community that went into lockdown because of a COVID-19 outbreak was successfully provided with diagnostic ultrasound access using a telerobotic ultrasound system [14].

Improving access to ultrasound imaging is especially important for Indigenous populations, many of whom live in rural and remote communities. Cultural and historical factors as well as other social determinants of health, such as low-income, substandard housing, food insecurity, and lack of transportation contribute to significant health disparities between Indigenous and non-Indigenous peoples [1,16-18]. Remote presence and virtual care technologies are considered a culturally safe method of providing care to Indigenous communities, because it allows patients to stay in their home communities [19]. Our study suggests that telerobotic ultrasound is well accepted by most patients, although a few patients expressed some initial apprehension with the technology, reporting that the ultrasound examination "didn't seem real."

To our knowledge, the telerobotic ultrasound clinics described in this article are the first to have been developed in North America, providing a model for radiology practices to increase access to ultrasound services for patients in their region. Comparisons can be made to earlier reports of telerobotic ultrasound in some European communities. In a study from France, a telerobotic ultrasound system was used to perform abdominal, pelvic, carotid artery, thyroid, and lower extremity venous Doppler examinations at a medical center and seniors' home 50 km away from the hospital at which the sonographer was based. In this series, telerobotic ultrasound examinations were successful in 97% of cases [20]. The lower proportion of examinations deemed adequate in our study may be secondary to experience of the operators (sonographers and patient-site assistants) and the potentially higher standard to which ultrasound examinations were subjected to in our study. In another study, Arbeille et al used motorized probes to scan the abdomen and pelvis, vascular structures, and small parts (thyroid and muscle) and perform obstetrical examinations. Images were deemed to be sufficient for diagnosis in 97% of cases in that series as well [21]. In Sweden, use of a telerobotic ultrasound system for echocardiography together with teleconsultation was found to decrease the total process time for cardiology consultation for patients with heart failure [22]. Further research should also explore the cost-effectiveness of telerobotic ultrasound services in a North American context.

This study provides insights into the types of examinations that are most suitable to be performed using a telerobotic ultrasound system. Diagnostic quality of abdominal, renal, first-trimester obstetrical, and limited obstetrical telerobotic ultrasound examinations was satisfactory in most cases; however, a large proportion of second-trimester obstetrical ultrasound examinations were recommended to be repeated. Although recommending a follow-up examination to ensure all fetal anatomy is adequately assessed is common even when performing conventional ultrasound, the high number of examinations with one or more fetal structures inadequately assessed resulted in a completion rate of only 25% in our study. In the literature, completion rates of a comprehensive anatomic survey are as low as 43% in normal weight individuals and 31% in class III obese individuals [23]. As previously discussed, increased body habitus (38% of the patients in our study were subjectively overweight or obese) and challenges in angulating the ultrasound probe using the telerobotic ultrasound system likely contributed to the lower-than-expected completion rate. Pelvic examinations were also limited because endovaginal scanning was not possible using the telerobotic ultrasound system.

The recent regulatory clearance of a telerobotic ultrasound system by the US FDA and Health Canada [24,25] provides an opportunity for radiology practices to develop telerobotic ultrasound clinics to improve access to imaging for underserved patients in their region. Hardware and software at a sonographer site can be used to connect with multiple patient sites, providing the opportunity to reach a greater number of communities. Having a dedicated team to support the telerobotic ultrasound clinics, including radiologists, sonographers, patient-site assistants, IT technicians, clinic coordinators, and health system administrators, with strong communication among all team members, will be important in resolving any challenges encountered. For example, initial delays in initiating one of the telerobotic ultrasound clinics because of barriers in integrating one of the ultrasound machines into the provincewide PACS and radiology information system was resolved with involvement of key health system leaders in the remote community and at our academic medical center. Collaboration with local community leadership will be critical to ensure deployment in a culturally safe manner.

Consideration needs to be given to the economic implications for radiology practices developing telerobotic ultrasound clinics, including initial setup costs and reimbursement. Incremental costs associated with telerobotic ultrasound relative to conventional ultrasound—beyond initial purchase of the equipment—include increased sonographer costs related to longer examination duration, potentially higher maintenance costs, and costs for an assistant at the patient site. It should be noted that this study was conducted in a single-payer health system with universal coverage for health services. It remains to be determined how various health systems and payers will determine reimbursements for telerobotic ultrasound examinations. Although our current experience with telerobotic ultrasound has been in underserved rural and remote communities in Canada, the potential of this technology to be used in low-resource jurisdictions around the globe must be explored.

There are some limitations to the study. First, only telerobotic examinations were performed for patients, and we were not able to compare diagnostic accuracy of telerobotic ultrasound to conventional ultrasound. However, these differences have been previously highlighted in the literature [8,9], and the purpose of this study was to consider the clinical practice management considerations of implementing telerobotic ultrasound in a real-world setting. Second, the measure of whether a conventional ultrasound is recommended is dependent on the reporting practices of the interpreting radiologist and will inherently vary between radiologists and practice settings. Third, the deployment of telerobotic ultrasound clinics in three communities provides some degree of generalizability of findings; however, experiences in deployment may vary across radiology practices, communities, and geographic regions.

TAKE-HOME POINTS

- Telerobotic ultrasound clinics were successfully deployed in three remote communities; using telerobotic technology, sonographers remotely manipulated an ultrasound probe using a 3-DOF robotic arm and remotely performed ultrasound examinations.

- Telerobotic ultrasound examinations successfully answered clinical questions in most cases, allowing patients to receive imaging in their home community without traveling to another city or waiting for an itinerant sonographer to visit their community.
- Telerobotic ultrasound clinics may improve access to ultrasound imaging in rural and remote communities in which ultrasound services are not otherwise available.

ACKNOWLEDGMENTS

We thank the many staff in Stony Rapids, La Loche, and Pelican Narrows who have provided ongoing assistance as telerobotic ultrasound clinics were launched in these communities. We thank Luis Bustamante and Joseph Deason for their technical assistance with the telerobotic ultrasound systems, Rachel Johnson for coordinating the telerobotic ultrasound clinics, and Nadine Kanigan and Jen Kesler as sonographers for the telerobotic ultrasound clinics. We are grateful for funding received from the Saskatchewan Health Research Foundation and Saskatchewan Centre for Patient-Oriented Research to support this study.

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