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Canadian Association of Radiologists Journal xx (2016) 1−7

CANADIAN ASSOCIATION OF RADIOLOGISTS JOURNAL

www.carjonline.org

Ultrasonography / Échographie

Initial Experience Using a Telerobotic Ultrasound System for Adult Abdominal Sonography

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Abstract

Purpose: The study sought to assess the feasibility of performing adult abdominal examinations using a telerobotic ultrasound system in which radiologists or sonographers can control fine movements of a transducer and all ultrasound settings from a remote location.
Methods: Eighteen patients prospectively underwent a conventional sonography examination (using EPIQ 5 [Philips] or LOGIQ E9 [GE Healthcare]) followed by a telerobotic sonography examination (using the MELODY System [AdEchoTech] and SonixTablet [BK Ultrasound]) according to a standardized abdominal imaging protocol. For telerobotic examinations, patients were scanned remotely by a sonographer 2.75 km away. Conventional examinations were read independently from telerobotic examinations. Image quality and acceptability to patients and sonographers was assessed.
Results: Ninety-two percent of organs visualized on conventional examinations were sufficiently visualized on telerobotic examinations. Five pathological findings were identified on both telerobotic and conventional examinations, 3 findings were identified using only conventional sonography, and 2 findings were identified using only telerobotic sonography. A paired sample *t* test showed no significant difference between the 2 modalities in measurements of the liver, spleen, and diameter of the proximal aorta; however, telerobotic assessments overestimated distal aorta and common bile duct diameters and underestimated kidney lengths (P values $< .05$). All patients responded that they would be willing to have another telerobotic examination.
Conclusions: A telerobotic ultrasound system is feasible for performing abdominal ultrasound examinations at a distant location with minimal training and setup requirements and a moderate learning curve. Telerobotic sonography (robotic telesonography) may open up the possibility of remote ultrasound clinics for communities that lack skilled sonographers and radiologists, thereby improving access to care.

Résumé

But : L'étude visait à évaluer la possibilité d'examiner l'abdomen d'un adulte à l'aide d'un système d'échographie télérobotique qui permet aux radiologistes ou aux technologues spécialisés en échographie de contrôler à distance les mouvements fins d'un transducteur et tous les paramètres de l'échographie.
Méthodes : Dix-huit patients ont subi de façon prospective un examen échographique classique (à partir d'appareils EPIQ 5 [Philips] ou LOGIQ E9 [GE Healthcare]), suivi d'un examen échographique télérobotique (avec les systèmes MELODY [AdEchoTech] et SonixTablet [BK Ultrasound]), selon un protocole d'imagerie abdominale normalisé. Pour les examens télérobotiques, les patients ont été évalués par un technologue spécialisé en échographie situé 2,75 km plus loin. Les examens classiques et télérobotiques ont été évalués indépendamment. Les éléments évalués étaient la qualité de l'image et son acceptabilité pour les patients et les technologues spécialisés en échographie.
Résultats : Quatre-vingt-douze pour cent des organes visibles sur les examens classiques étaient suffisamment visibles sur les examens télérobotiques. Cinq constatations pathologiques ont été repérées dans les examens classiques et télérobotiques, trois dans les examens échographiques classiques seulement et deux uniquement lors des échographies télérobotiques. Un test *t* effectué sur un échantillon apparié

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http://dx.doi.org/10.1016/j.carj.2016.08.002

n'a montré aucune différence notable entre les deux types d'examens pour les mesures du foie, de la rate et du diamètre de l'aorte proximale. Cependant, les examens télérobotiques ont surestimé les diamètres de l'aorte distale et du canal cholédoque et sous-estimé la longueur des reins (valeurs $P < 0{,}05$). Tous les patients ont affirmé être disposés à passer un autre examen télérobotique.

Conclusions : Il est possible d'utiliser un système d'échographie télérobotique pour effectuer des examens échographiques abdominaux à distance, avec une formation et une configuration minimales, et selon une courbe d'apprentissage modérée. L'échographie télérobotique peut ouvrir la voie à la création de cliniques d'échographie à distance dans les collectivités où il n'y a pas assez de technologues spécialisés en échographie ou des radiologistes qualifiés, ce qui améliorerait l'accès aux soins.

Key Words: Remote presence; Robotics; Teleradiology; Telerobotic; Telesonography; Ultrasound

Sonography offers many advantages for medical imaging; however, a lack of trained sonographers in remote communities limits access to sonography for many patients. As a result, many patients must travel, or be transported, to secondary and tertiary care centres, which often delays diagnosis and subsequent treatment, burdens patients and their families, and increases health care costs. Teleradiology has made remote image interpretation possible provided sonographers are available at the patient's location; however, due to the operator dependency of sonography, the skills of the sonographer or radiologist generating images are paramount. Radiologists remotely interpreting studies may be unable to recall the patient to generate additional images, if required, after the patient has left the imaging facility.

Telerobotic ultrasound systems allow sonographers or radiologists to remotely manipulate a transducer and generate images in real-time via an internet connection. Clinical studies mainly originating in France and Sweden have trialed telerobotic ultrasound systems for abdominal and pelvic [1], obstetric [2], vascular [3], and cardiac [4,5] applications, as well as imaging of the thyroid, carotid artery, and leg veins [6]. Prototypes used in these early studies allowed users to control fine movements of the ultrasound transducer by manipulating a mock probe; however, settings such as depth and gain were adjusted by an assistant at the patient site at the request of the sonographer. Another system, designed in North America, used a computer mouse to control movement of the transducer and was successfully used for imaging of the carotid artery [7].

In this study, we trial a new telerobotic ultrasound system consisting of a robotic arm (MELODY System; Société AdEchoTech, Naveil, France), an ultrasound system (SonixTablet; BK Ultrasound, Richmond, Canada), and a videoconferencing system (TE30 All-in-One, HD Videoconferencing Endpoint; Huawei Technologies, Shenzhen, China). By manipulating a mock probe at a distant site, a sonographer can control fine movements of the scanning transducer in real-time via movement of the robotic arm to which the transducer is attached. In contrast with systems trialed in previous studies, all settings on the ultrasound system can be adjusted by the remote sonographer using a monitor identical to the display on the ultrasound system at the patient site. The videoconferencing system allows the sonographer to communicate with the patient during the examination and communicate directions to a patient site assistant regarding gross positioning of the robotic arm and amount of pressure exerted by the transducer on the patient's abdomen. As telerobotic technology has advanced significantly since earlier reports, we assess the feasibility of this new telerobotic system to perform complete abdominal examinations, ability of the system to generate images of diagnostic quality, and acceptability of the system to patients and sonographers.

Methods

Study Cohort

Our institutional research ethics board approved the study and written consent was obtained from all participants. Nineteen patients, scheduled for routine abdominal sonography examinations at an imaging clinic (Saskatoon Medical Imaging), were prospectively recruited for this study in December 2015. Patients ≥18 years of age with an abdominal ultrasound examination scheduled for any clinical indication were identified. Patients were recruited consecutively provided a distant sonographer was available to scan at the time the patient presented for his or her examination. One participant was excluded from analysis as the telerobotic imaging protocol was not followed due to the sonographer's inexperience with the required protocol. Fourteen women (mean 45.3 years of age, range 18-85 years of age) and 4 men (mean 38.8 years of age, range 23-53 years of age) were included in the analysis. The mean age for all participants was 42.9 years.

Telerobotic System

A sonography room at the community imaging clinic was equipped with a SonixTablet ultrasound system and 5 MHz transducer, robotic arm, and electronic control box; the latter 2 components comprised the MELODY Patient System (Figure 1A). Our academic health sciences centre 2.75 km away served as the sonographer or radiologist site; a room was equipped with the MELODY Expert System (consisting of a mock probe and electronic control box) and a touch-screen monitor which displayed the ultrasound system interface identical to that displayed on the SonixTablet at the patient site (Figure 1B). This enabled the sonographer to control all settings such as gain, depth, and focus using either the

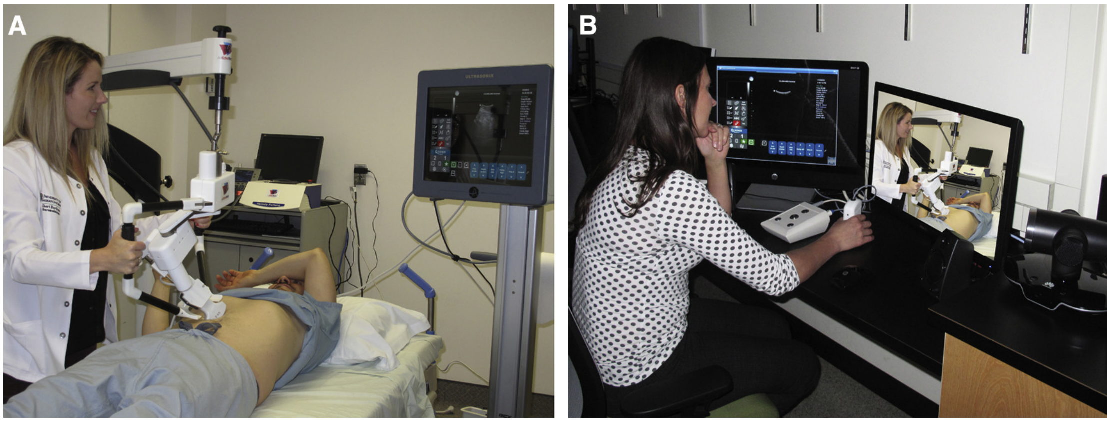

Figure 1. (A) At the patient site, an assistant holds the frame for the robotically controlled ultrasound transducer on the patient's abdomen. The videoconferencing system allows for communication between the sonographer and the patient and patient site assistant, enabling the patient site assistant to adjust pressure and gross placement of the robotic arm based on instructions from the sonographer. (B) At the sonographer site 2.75 km away, the sonographer manipulates a mock transducer; all movements of the mock transducer are replicated by the robotically controlled transducer at the patient site. The interface of the SonixTablet ultrasound system is displayed at the sonographer site, allowing the sonographer to scan in real time and control all ultrasound settings (image edited).

touch-screen monitor or a mouse. All fine movements of the mock probe (rotating, rocking, and tilting) were reproduced by the ultrasound probe at the patient site via the robotic arm.

The videoconferencing system enabled communication between the sonographer and the patient and patient site assistant. Gross placement and pressure of the robotic arm and transducer on the patient's abdomen was adjusted by the patient site assistant. The patient site assistant had no prior experience in ultrasound or patient care. The sonographer provided instructions to the patient site assistant on placement of the robotic probe holder using simple anatomical landmarks in lay language. Through the videoconferencing system the sonographer could observe the patient and gross placement of the robotic arm on the patient's abdomen. A nondedicated internet connection connected the 2 sites, with separate ports for the MELODY system and the videoconferencing system.

Sonographer Training and Scanning Protocol

Four sonographers received a 90-minute training session on use of the SonixTablet and MELODY System prior to commencement of the study. All patients included in the study were initially scanned using a conventional ultrasound system (EPIQ 5; Philips, Amsterdam, The Netherlands; or LOGIQ E9; GE Healthcare, Chicago, IL) according to a standardized abdominal imaging protocol; this provided a comparator for telerobotic sonography (robotic telesonography). Immediately following the conventional examination, patients were scanned by a different sonographer with similar experience and qualifications using the telerobotic system and the same imaging protocol, blinded to the findings of the conventional examination. The duration of each exam was recorded. All patients were scanned at a community imaging clinic for telerobotic and conventional examinations, whereas remote sonographers were based at our academic health sciences centre for telerobotic examinations. Each sonographer performed 2-6 telerobotic examinations, and the same patient site assistant assisted with all telerobotic scans.

Image Interpretation

Images in DICOM format were transferred from the SonixTablet to a USB flash drive or transferred directly to the local PACS and read by a board-certified radiologist (B.B.) using OsiriX (www.osirix-viewer.com) or Synapse (Fujifilm Holdings, Tokyo, Japan) for telerobotic and conventional examinations, respectively. Images were read independently from images obtained from the corresponding examination, and a standardized form broadly based on Stenman et al. [8,9] was used for reporting each examination. The reader also assessed whether each organ was sufficiently visualized based on the acquired images. Hepatorenal indices were calculated as previously described [10].

Patient Assessment

Following completion of both scans, patients completed a survey regarding their experience with the telerobotic examination. Participants were asked to indicate their agreement using a 5-point Likert-type scale with the following 4 statements: 1) If in the future I required another ultrasound study and sonography was not available in my community, I would be willing to have a robotic telesonography scan; 2) I felt comfortable communicating with the remote sonographer using the videoconferencing system; 3) I felt comfortable knowing that a person in a different room was controlling the ultrasound probe; and 4) I felt less pressure on my abdomen during the robotic telesonography study than I did during the conventional study.

Sonographer and Patient Site Assistant Assessment

Following each telerobotic examination, sonographers were asked to indicate their agreement using a 5-point Likert-type scale with the following 3 statements: 1) The audio was of sufficient quality to allow me to adequately communicate with the patient site assistant; 2) The patient site assistant and I were able to effectively communicate regarding probe or patient positioning; and 3) Manipulating the remote ultrasound probe resulted in less physical strain than scanning a similar patient using conventional sonography. Similarly, after each telerobotic examination the patient site assistant indicated her level of agreement with the following statements: 1) The audio was of sufficient quality to allow me to adequately communicate with the remote sonographer; 2) The sonographer and I were able to effectively communicate regarding probe or patient positioning; and 3) Holding the MELODY system caused moderate or severe physical strain (ie, I felt tired or sore as a result of holding the MELODY system).

Statistical Analysis

Descriptive statistics (mean values, standard deviations, and mean differences for continuous variables; frequencies and proportions for categorical responses) were determined. Measurements of structures and hepatorenal indices from conventional and telerobotic exams were compared using both a paired-sample *t* test and Wilcoxon signed rank test; the latter was performed to confirm the conclusions of the parametric *t*-test comparisons given that the small sample size made the assumption of normality for continuous variables questionable. Assessments for different patients made by the same sonographer were assumed to be independent. A significance threshold of $P < .05$ was used. Analysis was performed using SPSS version 23 (IBM, Chicago, IL).

Results

Duration of Examinations

The mean duration of telerobotic examinations was 39.9 minutes (range 27-58 minutes), compared to 15.7 minutes (range 7-25 minutes) for conventional examinations. The duration of each examination decreased an average of 21% from each sonographer's first examination to last examination as they gained additional experience with the system.

Image Assessment

Organs most reliably visualized using the telerobotic ultrasound system (given the organ was sufficiently visualized on the conventional examination) were the liver (18 of 18), bile duct (18 of 18), and right kidney (17 of 17), whereas the aorta (13 of 16), spleen (15 of 17), gallbladder (14 of 16), pancreas (14 of 16), and left kidney (15 of 17) were least reliably visualized. Five pathological findings were identified on both examinations (2 renal cysts, enlarged common bile duct, hepatic cyst, and a hyperechoic focus in the spleen), 3 findings were identified using only conventional sonography (a hepatic cyst, focal fatty sparing of the liver, and a small renal cyst), and 2 findings were identified using only telerobotic sonography (a small renal cyst and gallbladder wall polyp). Overall, images obtained using the SonixTablet appeared more hyperechoic as compared to those obtained using the EPIQ 5 and LOGIQ E9 ultrasound systems (Figures 2 and 3).

A paired-sample *t* test showed no significant difference between telerobotic and conventional measurements of liver span and diameters of the proximal aorta and spleen; however, telerobotic assessments overestimated distal aorta and common bile duct diameters and underestimated kidney lengths compared with the conventional scan (P values $< .05$) (Table 1). Additionally, there was a significant difference between hepatorenal indices calculated from images obtained using the telerobotic system as compared to the conventional system (Figure 4 and Table 1).

Patient Assessment

The telerobotic system was well received by participants. All patients strongly agreed or somewhat agreed with the

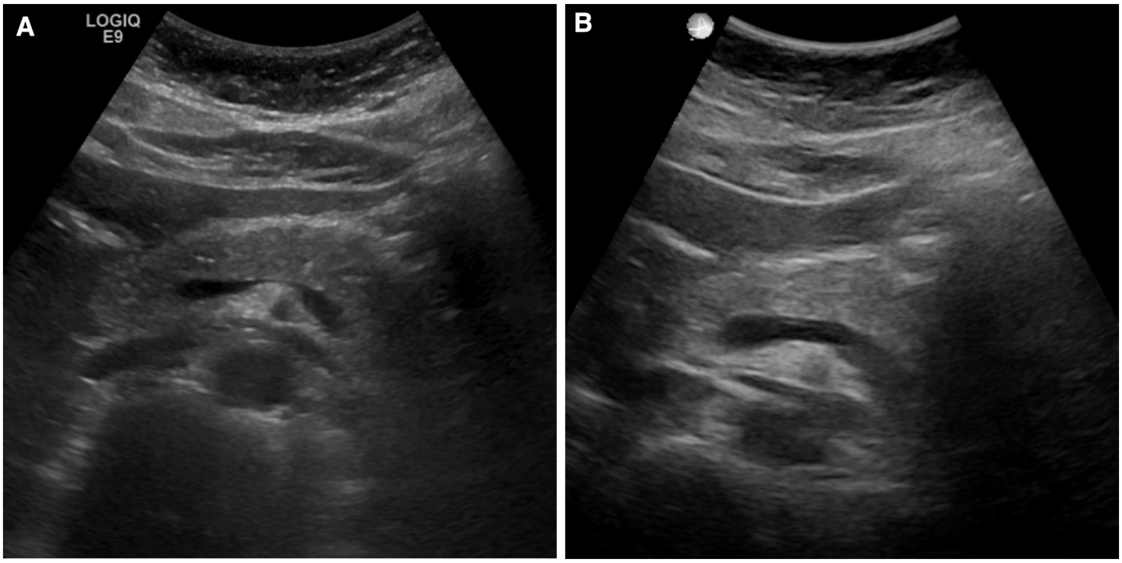

Figure 2. Transverse view of the pancreas in a 41-year-old woman obtained using the (A) LOGIQ E9 (conventional) ultrasound system and (B) SonixTablet/MELODY (telerobotic) system.

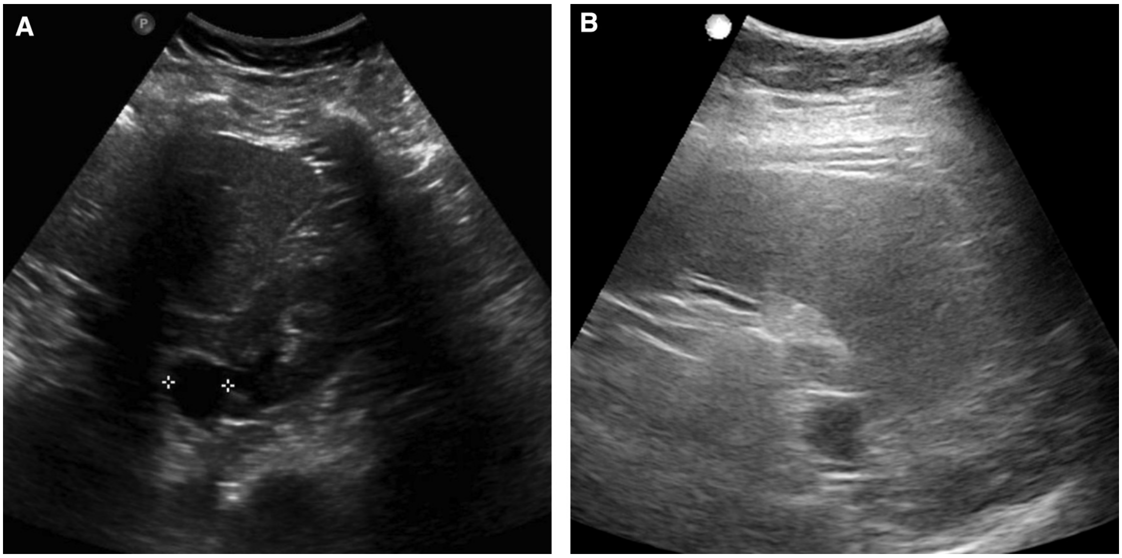

Figure 3. Transverse view of a 1.8-cm left renal cyst in a 45-year-old woman using the (A) EPIQ 5 (conventional) ultrasound system and (B) SonixTablet/MELODY (telerobotic) system. Overall, images from the telerobotic system were more hyperechoic than images from the conventional system.

statement that they would be willing to have a telerobotic scan in the future if conventional sonography was not available in their community (Table 2). A majority of participants felt comfortable communicating with the remote sonographer using the videoconferencing system and felt comfortable knowing that a person in a different room was controlling the ultrasound probe. Most participants agreed that they perceived less abdominal pressure during telerobotic examinations than during conventional exams; however, 5 participants were neutral or disagreed.

Sonographer and Patient Site Assistant Assessment

Sonographers and the patient site assistant reported the audio quality using the TE30 All-in-One, HD Videoconferencing Endpoint to be sufficient to communicate regarding gross placement of the robotic probe holder and patient positioning. Sonographers and the patient site assistant readily developed communication strategies with each other and for almost all examinations reported they were able to effectively communicate regarding probe or patient positioning. Sonographers were also able to gather additional medical history and provide patients with instructions regarding breathing or positioning through the videoconferencing system. Overall, sonographers found the telerobotic examinations were less physically demanding than conventional examinations as pressure of the transducer on the patient's abdomen was controlled by the patient site assistant, though the patient site assistant frequently noted moderate or severe physical strain after maintaining the robotic arm on the patient's abdomen for extended periods (Table 2).

Discussion

We demonstrated that a telerobotic ultrasound system in which sonographers can control fine movements and all ultrasound settings is feasible for performing abdominal ultrasound examinations at a distant location. Duration of examinations was longer for telerobotic examinations, though patients generally accepted the technology and would be willing to undergo another telerobotic examination. Visualization of abdominal organs was generally sufficient, though due to either limited range of motion of the probe or the quality of the

Table 1
Measurements of common structures and hepatorenal indices as determined using telerobotic and conventional sonography

Measurement	Telerobotic mean measurement	Conventional mean measurement	n[a]	Mean difference[b]	Paired *t*-test *P* value	Wilcoxon signed rank *P* value
Aorta diameter, proximal (mm)	17.4 ± 2.9	15.9 ± 3.4	15	1.5 ± 4.1	.19	.05
Aorta diameter, distal (mm)	15.7 ± 3.3	12.2 ± 2.1	13	3.5 ± 2.9	**.001**	**.005**
Common bile duct (mm)	5.0 ± 2.7	3.8 ± 2.4	16	1.2 ± 1.1	**.001**	**.004**
Spleen (cm)	9.8 ± 1.8	10.1 ± 1.9	17	−0.3 ± 1.0	.19	.10
Liver (cm)	13.5 ± 2.1	13.0 ± 2.0	16	0.5 ± 2.1	.36	.44
Right kidney, sagittal length (cm)	10.2 ± 1.0	10.7 ± 0.9	18	−0.5 ± 0.8	**.02**	**.02**
Left kidney, sagittal length (cm)	10.4 ± 0.9	11.0 ± 0.8	16	−0.6 ± 0.8	**.01**	**.02**
Hepatorenal index	1.2 ± 0.2	1.7 ± 0.5	15	−0.5 ± 0.6	**.004**	**.006**

Values are mean ± SD. Statistically significant differences ($P < .05$) are bolded.
[a] Number of paired robotic-conventional assessments.
[b] Robotic measurement minus conventional measurement.

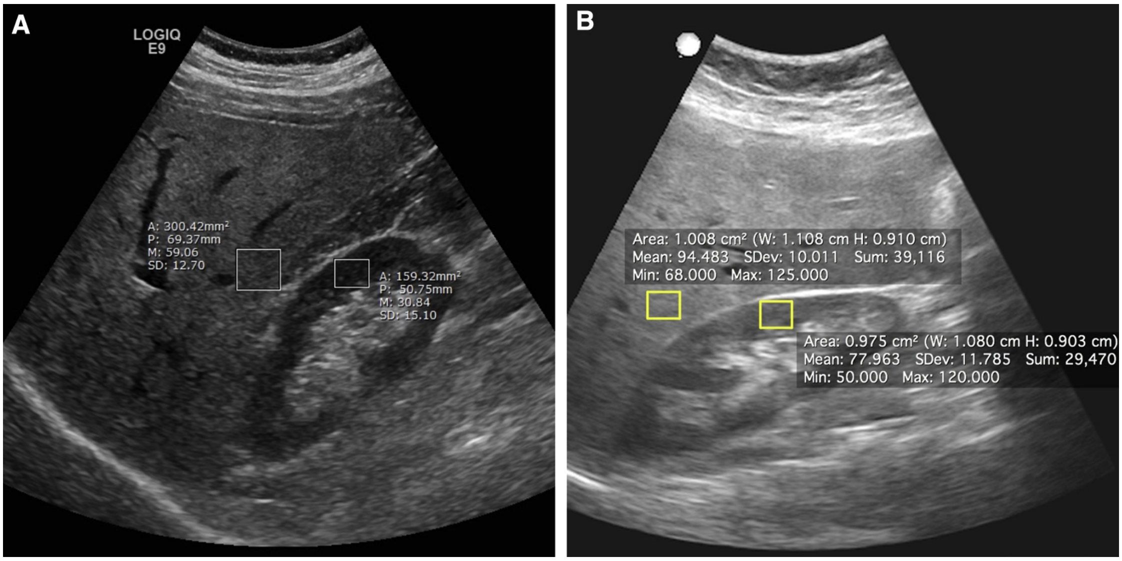

Figure 4. Regions of interest used to calculate the hepatorenal index for a 41-year-old female based on images obtained using the (A) LOGIQ E9 ultrasound system (conventional) and (B) SonixTablet/MELODY system (telerobotic).

ultrasound processing system, some small findings were not identified using the telerobotic system. However, there were also lesions unequivocally identified using the telerobotic system, which were not identified on the conventional examination, emphasizing the user dependency of sonography. The differences in measurements of common structures between the telerobotic and conventional examinations may be attributed to variation in underlying sonography equipment. For example, sonographers noted difficulty in precisely placing calipers on the touchscreen SonixTablet. Additionally, there is variation of measuring structures using different views or variance in technique between sonographers. The significant differences observed in hepatorenal indices may be due to measuring pixel brightness on images, which were not optimized for image quality, as it was noted that many of the sonographers did not fully adjust settings such as time gain compensation as on the standard conventional system due to the additional multiple steps required using the SonixTablet interface.

In contrast with previously reported telerobotic systems which use a computer mouse for movement of the probe [7],

Table 2
Patient, sonographer, and patient site assistant responses following conventional and telerobotic examinations

	Strongly agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Strongly disagree
Patients					
(1) If in the future I required another ultrasound study and sonography was not available in my community, I would be willing to have a robotic telesonography scan	16 (89)	2 (11)	0 (0)	0 (0)	0 (0)
(2) I felt comfortable communicating with the remote sonographer using the videoconferencing system	14 (78)	4 (22)	0 (0)	0 (0)	0 (0)
(3) I felt comfortable knowing that a person in a different room was controlling the ultrasound probe	14 (78)	2 (11)	2 (11)	0 (0)	0 (0)
(4) I felt less pressure on my abdomen during the robotic telesonography study than I did during the conventional study	7 (39)	6 (33)	2 (11)	3 (17)	0 (0)
Sonographers					
(1) The audio was of sufficient quality to allow me to adequately communicate with the patient site assistant	17 (94)	1 (6)	0 (0)	0 (0)	0 (0)
(2) The patient site assistant and I were able to effectively communicate regarding probe or patient positioning	14 (78)	3 (17)	0 (0)	1 (6)	0 (0)
(3) Manipulating the remote ultrasound probe resulted in less physical strain than scanning a similar patient using conventional sonography	4 (22)	7 (39)	3 (17)	3 (17)	1 (6)
Patient site assistant					
(1) The audio was of sufficient quality to allow me to adequately communicate with the remote sonographer	17 (94)	1 (6)	0 (0)	0 (0)	0 (0)
(2) The sonographer and I were able to effectively communicate regarding probe or patient positioning	16 (89)	0 (0)	1 (6)	1 (6)	0 (0)
(3) Holding the MELODY system caused moderate or severe physical strain (i.e. I felt tired or sore as a result of holding the MELODY system)	1 (6)	14 (78)	2 (11)	1 (6)	0 (0)

Values are n (%).

the telerobotic system trialed in this study used a transducer similar in appearance to that used conventionally, allowing scanning skills to be more easily transferred to operate the telerobotic system. Technical limitations of the present system include the inability for the sonographer to control pressure and sliding of the transducer, resulting in the need for a patient site assistant to apply pressure and grossly place the robotic arm on the patient's abdomen. However, we demonstrated that an individual with no healthcare background can sufficiently place the robotic arm when given instructions via the videoconferencing system by the sonographer.

The cost of the telerobotic ultrasound system described is comparable to a high-end ultrasound system. Further analysis is required to determine the cost-effectiveness of remote sonography, and must also take into account the increased time and human resources associated with the technique, the potential to minimize the number of patient transports to larger centres, and the ability to provide services such as prenatal imaging, which may be neglected if not otherwise available in patients' home communities. Another consideration is the inclusion of remote sonography on fee schedules, recognizing the additional resources telerobotic sonography currently entails.

There are several limitations related to inherent study design. First, differences in diagnostic performance cannot solely be attributed to the method of scanning (telerobotic versus conventional) because ultrasound systems of differing quality were used for each type of examination (SonixTablet for telerobotic examinations and EPIQ 5 or LOGIQ E9 for conventional examinations). However, this study does evaluate the telerobotic system as it would likely be used in a low-volume centre where an ultrasound system similar in quality to the SonixTablet may be employed. Second, telerobotic and conventional scanning was conducted by different sonographers, allowing sonographers to be blinded to findings from the corresponding examination. However, variation in scanning technique and thus diagnostic findings may have been introduced due to this study design. Our small sample size and use of sonography—a user-dependent modality—as the control for telerobotic examinations limited our ability to determine the sensitivity and specificity of telerobotic sonography in detecting pathological findings. The relatively young mean age of the study group (42.9 years of age) contributed to the limited number of pathologic findings demonstrated on sonography. Finally, recruiting additional patients would allow us to determine the duration of exams once sonographers had more experience with the system, as it was noted that duration of exams continued to decrease throughout the study period.

This study has demonstrated the feasibility of the clinical use of telerobotic sonography. Its potential use in remote or low-volume centres may fill an unmet need of timely access to ultrasound services. Following this study and the experience gained, we are planning to develop a remote sonography clinic at our institution utilising telerobotic ultrasound systems placed in remote communities, enabling patients to access sonography in their home community and bridging the differential in care for remote populations. As remote presence technology for health care delivery is being developed [11], we envision a network of telerobotic ultrasound systems located in remote or low-volume centres to be serviced by sonographers at central telerobotic sonography clinics. Such clinics could provide routine examinations for patients in low-volume or underserviced communities, as well as facilitate after-hours imaging for emergent cases, possibly avoiding transport to a larger centre for imaging. In small to midsized centres, telerobotic sonography may also allow access to subspecialized sonography, which would otherwise be unfeasible to offer in centres with low patient volume.

Acknowledgements

The authors thank Martine Pringle, Cheryl Saunders, Schalk van Rensburg, and colleagues at Saskatoon Medical Imaging for facilitating the study at their clinic and the University of Saskatchewan Remote Medicine Program and Division of Northern Medical Services for providing funding for purchase of the ultrasound system.

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