Economic Evaluation of Telerobotic Ultrasound Technology to Remotely Provide Ultrasound Services in Rural and Remote Communities

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Introduction—Telerobotic ultrasound technology allows radiologists and sonographers to remotely provide ultrasound services in underserved areas. This study aimed to compare costs associated with using telerobotic ultrasound to provide ultrasound services in rural and remote communities to costs associated with alternate models.

Methods—A cost-minimization approach was used to compare four ultrasound service delivery models: telerobotic ultrasound (Model 1), telerobotic ultrasound and an itinerant sonographer (Model 2), itinerant sonographer without telerobotic ultrasound (Model 3), and travel to another community for all exams (Model 4). In Models 1–3, travel was assumed when exams could not be successfully performed telerobotically or by an itinerant sonographer. A publicly funded healthcare payer perspective was used for the reference case and a societal perspective was used for a secondary non-reference case. Costs were based on the literature and experience using telerobotic ultrasound in Saskatchewan, Canada. Costs were expressed in 2020 Canadian dollars.

Results—Average cost per ultrasound exam was \$342, \$323, \$368, and \$478 for Models 1, 2, 3, and 4, respectively, from a publicly funded healthcare payer perspective, and \$461, \$355, \$447, and \$849, respectively, from a societal perspective. In one-way sensitivity analyses, Model 2 was the lowest cost from a payer perspective for communities with population >2075 people, distance >350 km from the nearest ultrasound facility, or >47% of the population eligible for publicly funded medical transportation.

Conclusion—Health systems may wish to consider solutions such as telerobotic ultrasound and itinerant sonographers to reduce healthcare costs and improve access to ultrasound in rural and remote communities.

Key Words—cost analysis; economic evaluation; health equity; robotics; rural and remote; ultrasound

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Introduction

The provision of healthcare services, such as ultrasound imaging, in rural and remote communities is fundamentally challenged by the dispersion of the population over a large geographic region. Recruitment and retention of healthcare providers to meet healthcare needs, providing specialty expertise in a timely manner, and higher healthcare costs are some of the challenges faced by many northern, remote communities in Canada.[1–3] In communities without sufficient human or financial resources to have sonographers or radiologists routinely available on-site, patients often must travel, or be transported, to another community for imaging.[4] In other communities where an itinerant sonographer visits the community on a monthly basis, long wait times often result.[4]

Telerobotic ultrasound is a new technology which equips a sonographer or radiologist with the ability to remotely manipulate an ultrasound probe, control all ultrasound machine settings, and remotely perform an ultrasound exam (Figure 1).[5] Clinical trials which have demonstrated the feasibility of a telerobotic approach for performing abdominal and obstetrical ultrasound imaging[6,7] and recent commercialization of telerobotic ultrasound systems[8–10] have paved the way for the implementation of this technology in remote communities. Our group launched telerobotic ultrasound clinics in three northern, remote communities in Saskatchewan, Canada, including one which was used to provide critical ultrasound services during a COVID-19 outbreak.[11,12] Using this technology, patients were able to have some ultrasound exams in their home communities (Figure 2), providing timely access to ultrasound imaging and minimizing patient travel.[12]

To inform the implementation of telerobotic ultrasound technology in health systems, it is critical to explore its cost impact compared with other models of providing ultrasound services. The objective of this study was to compare costs associated with using current telerobotic ultrasound technology to provide ultrasound services in rural and remote communities to costs associated with alternate models of ultrasound service provision, including having all patients travel to another city for ultrasound imaging or providing ultrasound services in combination with an itinerant sonographer.

Methods

As all data sources were publicly available, research ethics board approval and patient consent were not required to conduct the cost analysis. Patient consent and University of Saskatchewan Research Ethics Board approval were obtained to allow for representative images acquired using the telerobotic ultrasound system to be included in the manuscript.

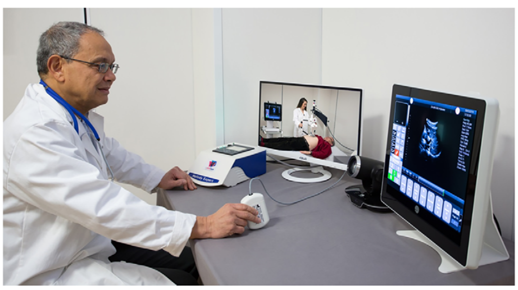
Study Design, Time Horizon, and Perspective

Equivalent diagnostic ultrasound performance between telerobotic and conventional methods was assumed when a radiologist did not recommend repeating the exam conventionally due to an exam deficiency. This assumption was based on the results

Figure 1. Telerobotic ultrasound system to remotely perform ultrasound exams. (**A**) At the patient-site, an ultrasound probe is attached to a 3-degrees-of-freedom robotic arm. An assistant at the patient-site holds the frame for the robotic arm and maintains sufficient pressure of the ultrasound probe on the patient's body. (**B**) At the sonographer-site, a radiologist or sonographer manipulates a mock probe, and movements of the mock probe are replicated by the scanning ultrasound probe at the patient-site via the robotic arm. The radiologist or sonographer can control rotation, rocking, and tilting of the ultrasound probe, but does not receive force feedback on the amount of pressure applied by the ultrasound probe on the patient's body. They can also control all ultrasound settings required to remotely perform an ultrasound exam. (Images used with permission of AdEchoTech.)

A

B



from two crossover comparison studies in which patients had both conventional and telerobotic ultrasound exams performed, with pathologic findings and measurements directly compared between the two methods of scanning.[6,7] These studies evaluated abdominal ultrasound exams and first, second, and third trimester obstetrical ultrasound exams. With the exception of second trimester obstetrical ultrasound exams, no clinically significant differences in diagnostic performance were appreciated between telerobotic and conventional methods of scanning.[6,7] As such, health outcomes were considered to be equivalent across all ultrasound service delivery models and a cost-minimization analysis was chosen as the study design, similar to prior studies related to teleradiology and telerobotic ultrasound.[13–15] To ensure that the time horizon captured all potential differences in costs associated with the interventions being compared,[16] a time horizon of 12 years was used, as this is the longest life expectancy of the equipment considered in the analysis. All costs subsequent to ultrasound imaging, such as treatment costs following diagnosis, were considered to be equal across all models and were not incorporated into the analysis. Consistent with current guidance, a publicly funded healthcare payer perspective was taken for the reference case and a societal perspective was taken in a secondary, non-reference case analysis.[16]

Setting and Base Case Population

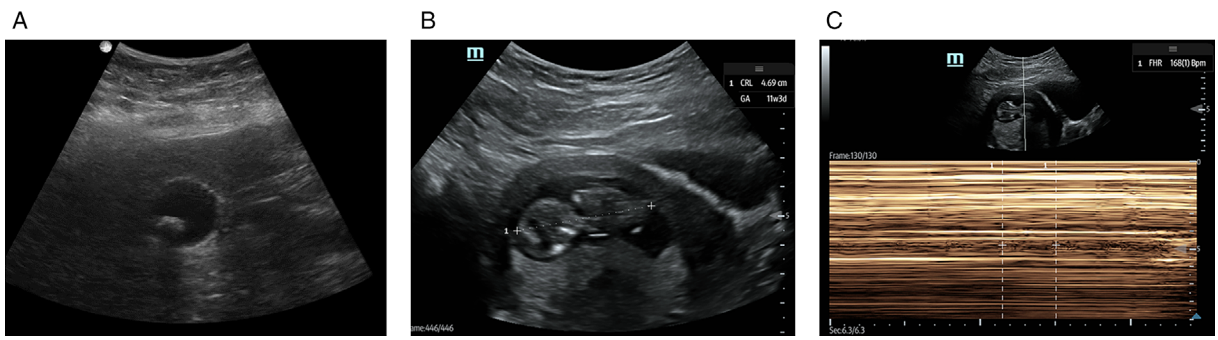
The base model assumed implementation of telerobotic ultrasound in a community representative of La Loche, a northern village in Saskatchewan, Canada, and a nearby First Nation also served by the La Loche Health Centre. This model assumed a community population of approximately 3200 people.[17,18] Using La Loche as the model community, the closest ultrasound facility with daily on-site ultrasound services was determined to be approximately 500 km away. Provincial per-capita utilization rates of the most common types of obstetrical and non-obstetrical exams were estimated based on Saskatchewan Ministry of Health Medical Services Branch physician billing data and exams included in the provincial Radiology Information System from January 1, 2014 to December 31, 2018. Ultrasound-guided procedures and subspecialized exams, including echocardiography and musculoskeletal ultrasound, were excluded from the analysis.

Ultrasound Service Delivery Models

Four service delivery models for the provision of ultrasound services in rural and remote communities were compared (Table 1).

Model 1 represents the predominant use of a telerobotic ultrasound system in a remote community to perform diagnostic ultrasound exams, with any exams that cannot be performed by the telerobotic ultrasound system being referred to another community. We assumed that on-call telerobotic ultrasound services were available 24 hours/day, 7 days/week, and that the telerobotic ultrasound clinics had sufficient capacity to meet demand in the community.

Figure 2. Representative images obtained using a telerobotic ultrasound system. (**A**) 54-year-old female with abdominal pain after eating greasy foods referred for an abdominal ultrasound; query cholelithiasis. Ultrasound demonstrated multiple mobile calculi within the gallbladder, the largest measuring 1.9 cm, with no features of cholecystitis. (**B**) 25-year-old female referred for a first trimester obstetrical ultrasound for dating. Ultrasound demonstrated a single intrauterine gestation with a crown-rump length of 4.69 cm, corresponding to a gestational age of 11 weeks 3 days. (**C**) From the same patient, fetal heart rate is 168 beats per minute.



Based on analysis of telerobotic ultrasound exams performed in three northern communities in Saskatchewan and weighted by the frequency of the most common exam types in Saskatchewan (including pelvic, abdominal, renal, superficial soft tissues, and first, second, and third trimester obstetrical exams), we assumed that radiologists would recommend that 27% of non-obstetrical and 16% of obstetrical exams (excluding second trimester complete obstetrical exams) be repeated conventionally due to limited visualization of some anatomic structures.[12] For exams in which the radiologist does not recommend that the exam be repeated conventionally, we assumed equivalent diagnostic performance between telerobotic and conventional methods based on prior studies.[6,7] As prior studies demonstrated suboptimal visualization of some structures as part of the second trimester fetal anatomic survey, we assumed that second trimester complete obstetrical exams were not performed using the telerobotic ultrasound system and any patients requiring a second trimester complete obstetrical exam were referred for a conventional exam in another community. We also assumed that any ultrasound exams that were recommended to be repeated conventionally following a telerobotic ultrasound exam were performed conventionally in another community to which the patient must travel.

We assumed that a non-dedicated receptionist was required at the patient-site to assist with patient registration for telerobotic ultrasound exams (5 minutes per patient) and an assistant was required for the duration of the exam (up to 1 hour per exam).

Model 2 similarly represents the deployment of a telerobotic ultrasound system in a remote community; however, any ultrasound exams that could not be performed using the telerobotic ultrasound system (including second trimester complete obstetrical exams) were performed by an itinerant sonographer who traveled to the community to perform ultrasound exams at a frequency necessary to meet ongoing demand. We assumed that the sonographer traveled to the community by air transportation (if traveling at least 350 km) or road transportation (if traveling less than 350 km) and performed an average of 12 ultrasound exams per day.[19]

Model 3 represents an itinerant sonographer visiting the community on a monthly basis (or as needed to meet total volumes). In this model, all urgent and emergent exams (Priority 1 and 2, such as acute abdominal pain, renal colic, or threatened abortion) require patients to travel, or be transported, to another community for imaging.[20] We assumed that 20% of obstetrical and non-obstetrical exams are Priority 1 or 2 and require patients to travel to another community for imaging,[20] and uncertainty in this point estimate due to local clinical practice variation was accounted for in a multiway probabilistic analysis.

Model 4 assumed that no ultrasound services were locally available, neither through telerobotic ultrasound clinics nor an itinerant sonographer, and

Table 1. Ultrasound service delivery models for rural and remote communities

	Telerobotic ultrasound	Itinerant sonographer	Travel to another community for imaging
Model 1 (Telerobotic ultrasound)	Available 24/7	Not available	Required for second trimester complete obstetrical exams and telerobotic exams recommended to be repeated conventionally
Model 2 (Telerobotic ultrasound and itinerant sonographer)	Available 24/7	Available on an interval basis	Required for urgent and emergent studies initially performed telerobotically but recommended to be repeated conventionally between the intervals in which a sonographer is on-site
Model 3 (Itinerant sonographer)	Not available	Available on an interval basis	Required for all urgent and emergent imaging between the intervals in which a sonographer is on-site
Model 4 (Travel required for all exams)	Not available	Not available	Required for all ultrasound imaging

that all patients requiring an ultrasound exam must travel to another community.

Cost Inputs

Cost estimates related to the performance of ultrasound exams using each of the four models are presented in Table 2 and Appendix S1. Costs were discounted at a rate of 1.5% per year based on current guidance from the Canadian Agency for Drugs and Technology in Health (CADTH).[16] All costs were expressed in 2020 Canadian dollars.

Primary Outcome and Sensitivity Analyses

The primary outcome was the average cost per ultrasound exam for each of the four service delivery models. To account for uncertainty in model parameters and cost estimates, 95% confidence intervals for the average cost per ultrasound exam for each of the four service delivery models were determined using probabilistic analysis. Model parameters and cost estimates were allowed to vary probabilistically within intervals derived from the literature and prior data, where available, in multiway probabilistic analyses (Table 3). Ten thousand simulations were performed and 95% confidence intervals were subsequently determined.

To consider generalizability to other communities where ultrasound services are not regularly available, one-way sensitivity analyses were conducted to determine differences in average cost per ultrasound exam as population, distance to the nearest facility with regular ultrasound services, proportion of the population eligible for publicly funded medical transportation, proportion of telerobotic exams which were recommended to be repeated, and frequency of itinerant sonographer visits varied.

Analyses were performed using Microsoft Excel 2010 (Redmond, Washington) and R (R Foundation for Statistical Computing, Vienna, Austria).

Results

Publicly Funded Healthcare Payer Perspective

The average cost per ultrasound exam from a publicly funded healthcare payer perspective was $342 (Model 1, in which telerobotic ultrasound is used to perform most ultrasound exams, with any ultrasound exams that cannot be performed by the telerobotic ultrasound system being referred to another community), $323 (Model 2, in which telerobotic ultrasound is used to perform most ultrasound exams, with any ultrasound exams that cannot be performed by the telerobotic ultrasound system being performed by an itinerant sonographer or referred to another community), $368 (Model 3, in which an itinerant sonographer performs most ultrasound exams, with any urgent ultrasound exams requiring patient travel to another community), and $478 (Model 4, in which all ultrasound exams are referred to another community to which patients must travel). Results from multi-way probabilistic analyses are presented in Table 4.

In a one-way sensitivity analysis as the community population size and corresponding volume of ultrasound exams increased, average cost per exam decreased for Models 1, 2, and 3, and was constant for Model 4 (Figure 3A). For communities with <535 people, Model 4 (having all patients travel to another community) was the lowest cost model, as no capital investment for an ultrasound unit or telerobotic ultrasound system was required for the remote community. For a population between 535 and 2075 people, Model 3 (itinerant sonographer model) was the lowest cost, and for a population greater than or equal to 2075 people, Model 2 (telerobotic ultrasound with an itinerant sonographer) was the lowest cost.

As the distance to the nearest ultrasound facility increased, the cost per ultrasound exam increased for all models, though the greatest increase was seen for Model 4, which relied exclusively on travel to another community for the provision of ultrasound services (Figure 4A). At shorter distances to the nearest ultrasound facility (<350 km), Model 4 (patient travel for all ultrasound exams) was least costly from a publicly funded healthcare payer perspective. At greater distances to the nearest ultrasound facility (>350 km), Model 2 (telerobotic ultrasound with an itinerant sonographer) was least costly from a publicly funded healthcare payer perspective as this model minimized travel costs.

For communities with <28% of the population eligible for publicly funded medical transportation, Model 4 (requiring travel for all ultrasound exams) was the lowest cost model from a publicly funded healthcare payer perspective (Figure 5A). For communities with between 28 and 47% of the population eligible for publicly funded medical transportation,

Table 2. Summary of cost inputs

	Total	Annualized	Per exam	Reference
A. Costs from a publicly funded healthcare payer perspective				
Ultrasound exams performed in a remote community using telerobotic ultrasound (included in Models 1 and 2 [excluding second trimester obstetrical ultrasound exams])				
Fixed costs				
Telerobotic ultrasound system (patient-site and sonographer-site)[a]	$ 154,000.00	$ 14,118.72		Personal communication (AdEchoTech)
Ultrasound machine[a]	$ 54,000.00	$ 6458.93		Personal communication (AdEchoTech)
Videoconferencing systems (patient-site and sonographer-site)[a]	$ 15,000.00	$ 1794.15		Personal communication (AdEchoTech)
Annual maintenance for all capital equipment (10% purchase price)[a]		$ 22,300.00		Halvorsen and Kristiansen[13] and personal communication (AdEchoTech)
Shipping of equipment to remote community[a]	$ 170.00	$ 20.33		Personal communication (Department of Surgery, University of Saskatchewan)
Patient-site assistant training (2 patient-site assistants × 1 hour each at $23.50/hour and 1 trainer × 2 hours at $45/hour; assuming staff turnover every 3 years)[a]	$ 137.00	$ 47.04		Personal communication (Department of Surgery, University of Saskatchewan)
Sonographer training (2 sonographers × 1 hour each at $60/hour and 1 trainer × 2 hours at $45/hour; assuming staff turnover every 3 years)[a]	$ 210.00	$ 72.11		Personal communication (Department of Surgery, University of Saskatchewan and Ultrasound Centre, Saskatoon)
Variable costs				
Sonographer salary and benefits (1 hour for each exam at $60/hour)[a]			$ 60.00	Personal communication (Ultrasound Centre, Saskatoon)
Patient-site assistant salary and benefits (1 hour for each exam at $23.50/hour)[a]			$ 23.50	Personal communication (Northern Medical Services)
Receptionist salary and benefits (5 minutes for each exam at $23.50/hour)[a]			$ 1.96	Personal communication (Northern Medical Services)
Radiologist interpretation fee (weighted average of non-obstetrical ultrasound exams)			$ 43.17	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Radiologist interpretation fee (weighted average of obstetrical ultrasound exams excluding second trimester complete exams)			$ 44.06	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Radiologist interpretation fee (second trimester obstetrical ultrasound exams)			$ 51.25	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Ultrasound exams performed in a remote community by an itinerant sonographer (included in Model 2 [for all second trimester obstetrical ultrasound exams and non-diagnostic, non-urgent/emergent telerobotic ultrasound exams] and Model 3 [for all non-urgent/emergent exams])				
Fixed costs				
Ultrasound machine[a]	$ 54,000.00	$ 6458.93		Personal communication (AdEchoTech)
Annual maintenance (10% purchase price)[a]		$ 5400.00		Halvorsen and Kristiansen[13]
Shipping[a]	$ 170.00	$ 20.33		Personal communication (Department of Surgery, University of Saskatchewan)
Variable costs				
Sonographer salary and benefits ($650 per clinic, with 12 ultrasound exams performed during one clinic)[a]			$ 54.17	Personal communication (Northern Medical Services)
Receptionist salary and benefits (5 minutes per exam at $23.50/hour)[a]			$ 1.96	Personal communication (Northern Medical Services)

(Continues)

Table 2. Continued

	Total	Annualized	Per exam	Reference
Radiologist interpretation fee (weighted average of non-obstetrical ultrasound exams)			$ 43.17	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Radiologist interpretation fee (weighted average of obstetrical ultrasound exams excluding second trimester complete exams)			$ 44.06	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Radiologist interpretation fee (second trimester complete ultrasound exams)			$ 51.25	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Sonographer air travel to community ≥350 km away ($7000 round trip charter flight shared among an average of 2.7 passengers, with an average of 12 ultrasound exams performed per trip, round-trip)[a]			$ 216.05	Personal communication (Northern Medical Services)
Sonographer automobile travel to community <350 km away ($0.49/km, with an average of 12 ultrasound exams performed per trip, round-trip)[a]			$ 14.29	Canada Revenue Agency[25]
Ultrasound exams performed using a conventional ultrasound machine at a facility to which patients must travel (included in Model 1 [for all second trimester obstetrical ultrasound exams and non-diagnostic telerobotic ultrasound exams], Model 2 [for all non-diagnostic, urgent/emergent telerobotic ultrasound exams], Model 3 [for all urgent/emergent exams], and Model 4 [for all ultrasound exams])				
Fixed costs				
None; all costs are considered to be incorporated into the technical component fee from the *Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]				
Variable costs				
Technical and interpretation fee (weighted average of non-obstetrical ultrasound exams)			$ 119.10	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Technical and interpretation fee (weighted average of obstetrical ultrasound exams excluding second trimester complete exams)			$ 119.05	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Technical and interpretation fee (second trimester complete ultrasound exams)			$ 138.40	*Payment Schedule for Insured services Provided by a Physician* for Saskatchewan[24]
Medical transportation costs (to ultrasound facility between 0 and 350 km from home community, round-trip)[b]			$ 243.64	Personal communication (Indigenous Services Canada)
Medical transportation costs (to ultrasound facility between 350 and 700 km from home community, round-trip)[a,b]			$ 609.62	Personal communication (Indigenous Services Canada)
Medical transportation costs (to ultrasound facility >700 km from home community, round-trip)[b]			$ 2834.00	Personal communication (Indigenous Services Canada)
B. Additional costs from a societal perspective				
Ultrasound exams performed using a conventional ultrasound machine at a facility to which patients must travel (included in Model 1 [for all second trimester obstetrical ultrasound exams and non-diagnostic telerobotic ultrasound exams], Model 2 [for all non-diagnostic, urgent/emergent telerobotic ultrasound exams], Model 3 [for all urgent/emergent exams], and Model 4 [for all ultrasound exams])				
Automobile travel ($0.49/km; assuming 1000 km round trip)[a]			$ 490.00	Canada Revenue Agency[25]

(Continues)

Table 2. Continued

	Total	Annualized	Per exam	Reference
Air travel (round trip)[a]			$ 855.00	Transwest Air[26]
Accommodation (1 night at $103.67/night)[a]			$ 103.67	CBRE Hotel Industry Statistics for Saskatchewan via Ontario Ministry of Tourism, Culture and Sport[27]
Meals (2 days at $69/day)[a]			$ 138.00	Canada Revenue Agency[25]
Lost income (0.5 days based on average income of $36,475)[c]			$ 49.97	Statistics Canada[17,18]
Lost income (2 days based on average income of $36,475)[c]			$ 199.87	Statistics Canada[17,18]
Child care ($41/day/child; assuming 0.5 days of child care are required)[a]			$ 20.50	Canadian Centre for Policy Alternatives[28]
Child care ($41/day/child; assuming 2 days of child care are required)[a]			$ 82.00	Canadian Centre for Policy Alternatives[28]

[a]All costs indicated with an asterisk were varied based on a gamma distribution in the reference case multiway probabilistic analysis.[29]
[b]Medical transportation costs included transportation, hotel accommodations, and meal vouchers, when available.
[c]Total income varied according to the actual distribution of 2015 total income (adjusted to 2020 Canadian dollars) based on the 2016 Census in the reference case multiway probabilistic analysis.

Table 3. Model parameters

Parameter	Base case value	Sensitivity analysis	Reference
Population and community characteristics			
Population size	3,200	Varied from 250 to 10,000 in a one-way sensitivity analysis. Held constant in the reference case multi-way probabilistic analysis.	Statistics Canada[17,18]
Distance to the closest ultrasound facility, km	500	Varied from <350 km, 350–700 km, and >700 km in a one-way sensitivity analysis. Held constant in the reference case multi-way probabilistic analysis.	—
Proportion of the population eligible for publicly funded medical transportation	59%	Varied from 0 to 100% in a one-way sensitivity analysis. Varied using a Bernoulli distribution in the reference case multi-way probabilistic analysis.	Statistics Canada[17,18]
Pregnancy rate per 1000 persons	20.2	Varied using a Poisson distribution (with a lower bound of 1) in the reference case multi-way probabilistic analysis.	Personal communication (Northern Saskatchewan Population Health Unit)
Proportion of population with children ≤14 years requiring childcare	32%	Varied using a Bernoulli distribution in the reference case multi-way probabilistic analysis	Statistics Canada[30]
Ultrasound rates			
Rate of non-obstetrical ultrasound visits per 1000 person-years	102	Varied using a Poisson distribution (with a lower bound of 1) in the reference case multi-way probabilistic analysis	Adams et al[31]

(Continues)

Table 3. Continued

Parameter	Base case value	Sensitivity analysis	Reference
Rate of obstetrical ultrasound visits (excluding second trimester complete exams) per 1000 pregnancies	2670	Varied using a Poisson distribution (with a lower bound of 1) in the reference case multi-way probabilistic analysis	Adams et al[32]
Rate of second trimester obstetrical ultrasound visits per 1000 pregnancies	631	Varied using a Poisson distribution (with a lower bound of 1) in the reference case multi-way probabilistic analysis	Adams et al[32]
Telerobotic ultrasound			
Proportion of non-obstetrical ultrasound exams performed using telerobotic ultrasound which are non-diagnostic	27%	Varied using a Bernoulli distribution in the reference case multi-way probabilistic analysis	Adams et al[12]
Proportion of obstetrical ultrasound exams (excluding second trimester complete exams) performed using telerobotic ultrasound which are non-diagnostic	16%	Varied using a Bernoulli distribution in the reference case multi-way probabilistic analysis	Adams et al[12]
Itinerant sonographer			
Ultrasound exams performed per day	12	Varied using a Poisson distribution in the reference case multi-way probabilistic analysis	Northern Medical Services[19]
Number of people traveling on the charter flight	2.7	Varied from 1 to 4 persons using a uniform distribution in the reference case multiway probabilistic analysis	Personal communication (Northern Medical Services)
Ultrasound priority			
Proportion of non-obstetrical ultrasound exams which are Priority 1 or 2	20%	Varied from 10 to 30% using a uniform distribution in the reference case multiway probabilistic analysis	Personal communication (University of Saskatchewan Department of Surgery/Northern Medical Services)
Proportion of obstetrical exams (excluding second trimester complete) which are Priority 1 or 2	20%	Varied from 10 to 30% using a uniform distribution in the reference case multiway probabilistic analysis	Personal communication (University of Saskatchewan Department of Surgery/Northern Medical Services)
Discount rate			
Discount rate	1.5%	Varied from 0 to 3% using a uniform distribution	CADTH[16]

Note: Costs presented in Table 2 were varied using a gamma distribution. Parameters α and β were determined using the method of moments approach.[29] The base cost value was assumed to represent the sample mean and the standard error was assumed to be 10% of the base cost value, similar to prior literature.[33]

Table 4. Average cost per ultrasound exam for the base case by ultrasound service delivery model

Model	Average cost per ultrasound exam from a publicly funded healthcare payer perspective (95% CI)	Average cost per ultrasound exam from a societal perspective (95% CI)
Model 1 (Telerobotic ultrasound)	\$342 (\$310–381)	\$461 (\$421–511)
Model 2 (Telerobotic ultrasound and itinerant sonographer)	\$323 (\$293–364)	\$355 (\$323–399)
Model 3 (Itinerant sonographer)	\$368 (\$327–430)	\$447 (\$391–520)
Model 4 (Travel required for all exams)	\$478 (\$412–555)	\$849 (\$764–932)

Abbreviation: CI, confidence interval.

Figure 3. Average cost per ultrasound exam for each ultrasound service delivery model from a (**A**) publicly funded healthcare payer perspective and (**B**) societal perspective as community population size varies. All other parameters are held constant in each model.

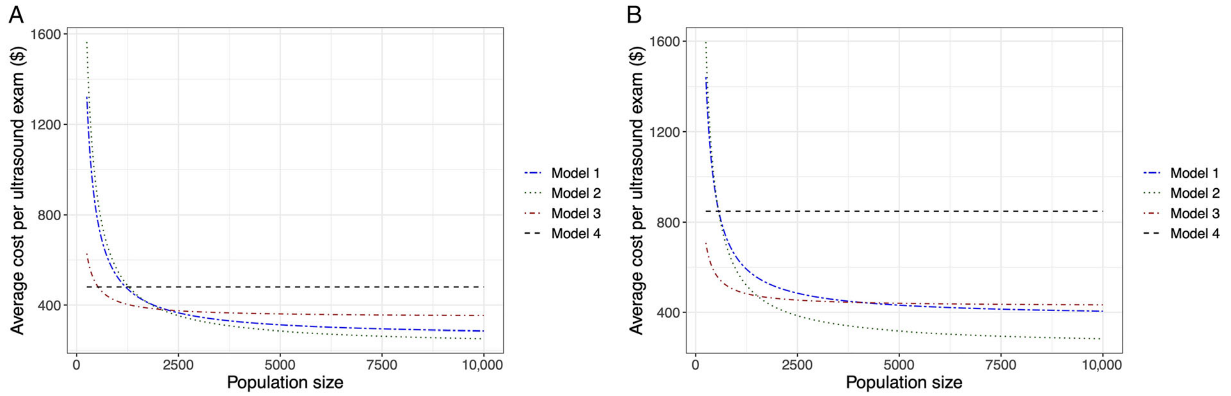


Figure 4. Average cost per ultrasound exam for each ultrasound service delivery model from a (**A**) publicly funded healthcare payer perspective and (**B**) societal perspective for communities <350 km, 350–700 km, and >700 km away from the closest ultrasound facility. All other parameters are held constant in each model.

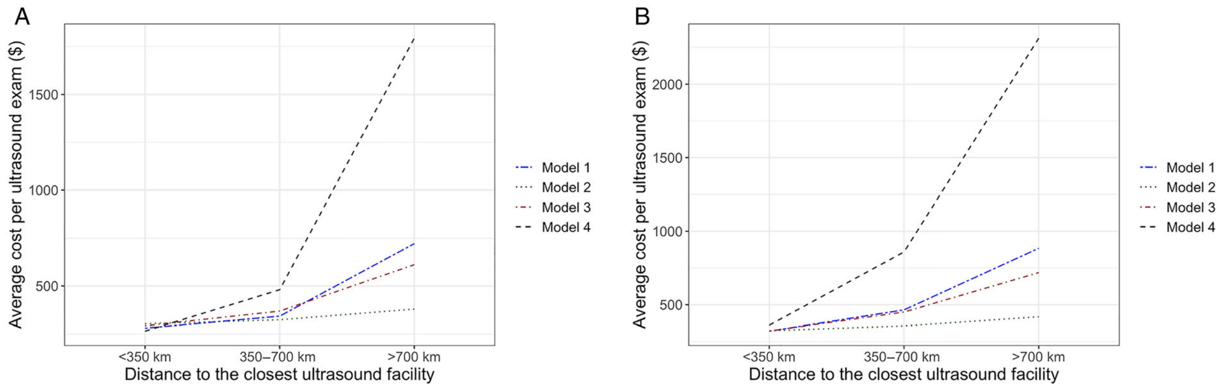
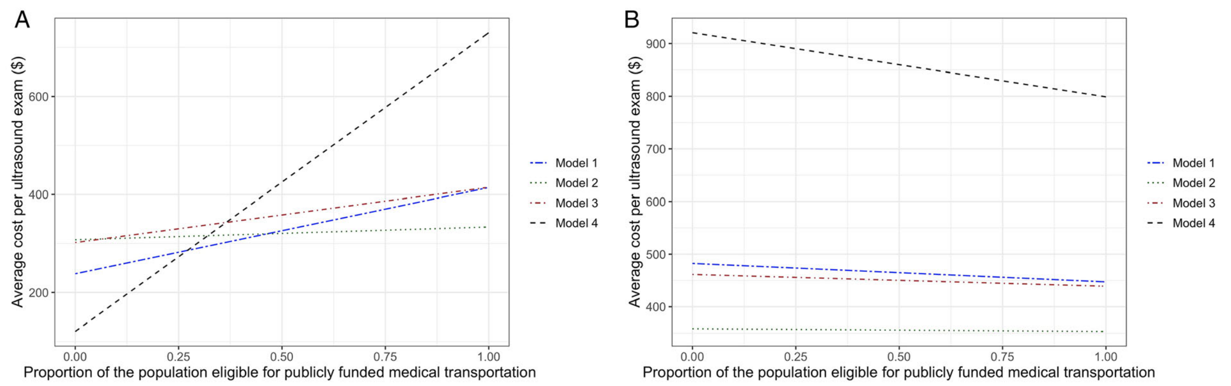


Figure 5. Average cost per ultrasound exam for each ultrasound service delivery model from a (**A**) publicly funded healthcare payer perspective and (**B**) societal perspective as the proportion of the population who are eligible for publicly funded medical transportation (status First Nations persons) varies. All other parameters are held constant in each model.



Model 1 (telerobotic ultrasound) was the lowest cost, and for communities with ≥47% of the population eligible for publicly funded medical transportation, Model 2 (telerobotic ultrasound with an itinerant sonographer) was lowest cost.

In the one-way sensitivity analysis as the proportion of telerobotic exams which were non-diagnostic and recommended to be repeated conventionally varied, Model 1 (telerobotic ultrasound) was the lowest cost model if the proportion of non-diagnostic telerobotic ultrasound exams was <8% (Figure 6A). Model 2 (telerobotic ultrasound with an itinerant sonographer) was the lowest cost model if between 8 and 37% of telerobotic exams were non-diagnostic, and Model 3 (itinerant sonographer) was lowest cost if the proportion of non-diagnostic exams was >37%.

In the one-way sensitivity analysis as the frequency of sonographer visits varied, Model 2 was the lowest cost model and at a minimum when the frequency of sonographer trips matched demand for ultrasound exams required to be performed by the itinerant sonographer, which was observed at a frequency of approximately every 4 weeks (Figure 7A). The average cost per ultrasound exam for Model 2 was higher with more frequent sonographer visits due to a lower volume of ultrasound exams being performed during each sonographer trip. The cost was also higher with less frequent sonographer visits due to more patients having to travel for ultrasound exams rather than have them be performed by the itinerant sonographer. Similarly, for Model 3, the average cost per ultrasound exam was at a minimum

Figure 6. Average cost per ultrasound exam for each ultrasound service delivery model from a (**A**) publicly funded healthcare payer perspective and (**B**) societal perspective as the proportion of telerobotic ultrasound exams which are non-diagnostic and are recommended to be repeated conventionally varies. All other parameters are held constant in each model.

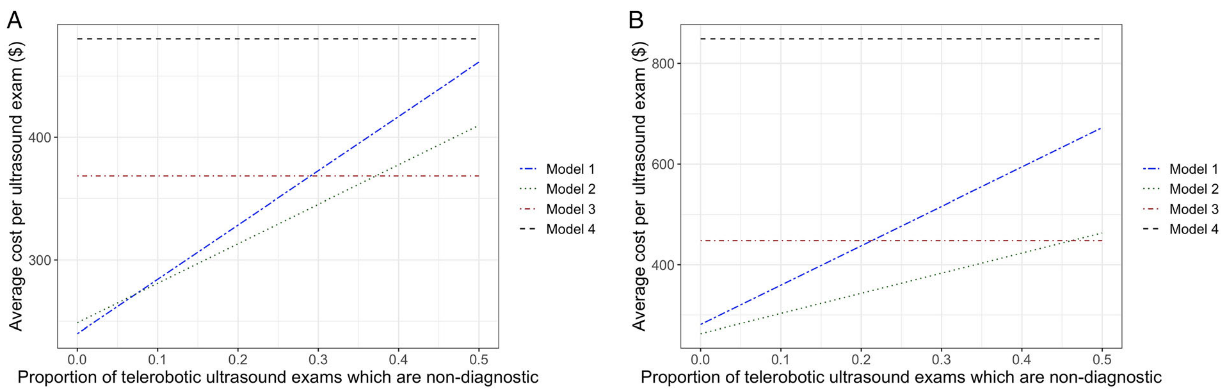
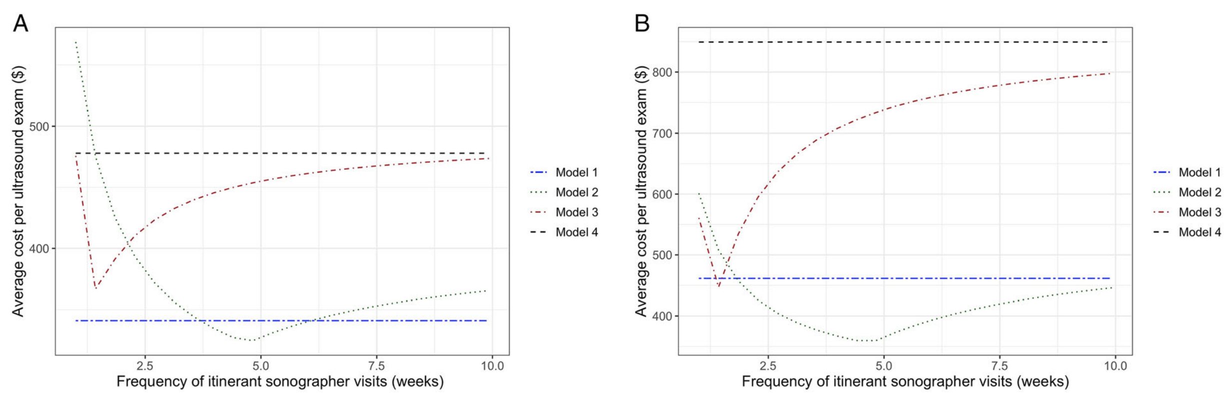


Figure 7. Average cost per ultrasound exam for each ultrasound service delivery model from a (**A**) publicly funded healthcare payer perspective and (**B**) societal perspective as the frequency of itinerant sonographer visits varies. All other parameters are held constant in each model.



when the frequency of sonographer trips matched demand for ultrasound exams in the community. Average cost per ultrasound exam was higher when itinerant sonographer trips were more frequent than required to meet the volume of ultrasound exams required in the community.

Societal Perspective

From a societal perspective, the average cost per ultrasound exam was $461, $355, $447, and $849 for Models 1, 2, 3, and 4, respectively (Table 4). In a one-way sensitivity analysis as community population size varied, Model 3 (itinerant sonographer) was the lowest cost model for communities with <1510 people (Figure 3B). For communities with ≥1510 people, Model 2 (telerobotic ultrasound with an itinerant sonographer) was lowest cost.

In another one-way sensitivity analysis as distance to the closest ultrasound facility was varied, for communities <350 km from the closest ultrasound facility, Model 3 (itinerant sonographer) was associated with the lowest cost (Figure 4B). For communities >350 km, Model 2 (telerobotic ultrasound with an itinerant sonographer) was the lowest cost model. Across all proportions of the population who were eligible for publicly funded medical transportation, Model 2 was the lowest cost model (Figure 5B).

In the one-way sensitivity analysis as the proportion of telerobotic exams that were non-diagnostic varied, Model 2 was the lowest cost model if the proportion of non-diagnostic telerobotic ultrasound exams was <47% (Figure 6B). Model 3 was the lowest cost model if 47%, or more, telerobotic exams were non-diagnostic. In the one-way sensitivity analysis as the frequency of itinerant sonographer trips varied, Model 2 was the lowest cost option from a societal perspective and at a minimum when the frequency of itinerant sonographer visits matched the required volume of ultrasound exams to be performed by the itinerant sonographer, similar to findings from a publicly funded healthcare payer perspective (Figure 7B).

Discussion

Economic analysis is one important consideration in determining the value of various models of providing ultrasound services to patients in rural and remote communities. This study found that having patients travel to another community for ultrasound services was the most costly option from both publicly funded healthcare payer and societal perspectives for certain communities, including those with greater populations, greater distances from an ultrasound facility, and greater proportions of the population eligible for publicly funded medical transportation. Service delivery models which brought ultrasound services closer to patients' own communities—either through telerobotic ultrasound and/or having an itinerant sonographer regularly visit the community—were lower cost options from publicly funded healthcare payer and societal perspectives for various communities when the frequency of itinerant sonographer visits matched required demand in the community. Due to the high initial capital investment required for a telerobotic ultrasound system, models that incorporated telerobotic ultrasound were more costly on a per-exam basis for communities with a smaller population and corresponding lower volume of exams. In addition, for communities relatively close to an ultrasound facility, having patients travel to an existing ultrasound facility was the lowest cost model on a per-exam basis because no investment in a telerobotic ultrasound system was required and costs for transportation were relatively lower.

A study conducted in Sweden found that telerobotic ultrasound for echocardiography and remote cardiac consultation was associated with slightly greater costs from a health system perspective than a traditional model where patients had to travel for imaging and consultation, though from a societal perspective, a remote model including telerobotic ultrasound was lower cost, primarily due to decreased patient transportation cost.[14] Our study found that a model including telerobotic ultrasound was lower cost from both publicly funded healthcare payer and societal perspectives than a model requiring patients to travel for all ultrasound exams. There are a multitude of reasons which may explain this difference, including differences in cost inputs and model parameters such as community size, type of ultrasound exams performed, and policy regarding patient travel reimbursement.

Prior research has described many challenges patients in northern, remote communities face when traveling for an ultrasound exam, including often having to travel alone without their partner or other family members being present for support, the need to take time off work and find reliable childcare, and fear of air travel. Incorporating these "costs" in the economic evaluation may further point to the favorability of Model 2 (combining telerobotic ultrasound with an itinerant sonographer), which allows a greater number of patients to remain in their home community for ultrasound. As recently demonstrated in three northern, remote communities in Saskatchewan, Canada, telerobotic ultrasound can offer underserved rural and remote communities ultrasound services across a wide range of exam types, including abdominal and pelvic/obstetrical, albeit with limitations for second trimester obstetrical ultrasound exams.[12] This technology may reduce travel for the majority of patients, reduce wait times, and reduce time to diagnosis, thereby addressing concerns shared among many patients in communities with limited access to ultrasound services.[4]

This cost analysis presents community leaders and healthcare decision makers with four scenarios as clinical options which may or may not be appropriate for all communities. Sonographer availability for an itinerant sonographer service, reliable transportation for sonographers to travel to the community, and cultural acceptability are key considerations. For remote communities which are geographically close to each other (but are located far from an ultrasound facility), a "hub and spoke" model could be utilized with a single telerobotic ultrasound system at the hub to also serve nearby communities. This could increase the volume of ultrasound exams performed using the central telerobotic ultrasound hub and reduce the average cost per ultrasound exam. In settings where telerobotic ultrasound is not available after hours, a greater proportion of patients would have to travel or be transported to another community for imaging, increasing the average cost per ultrasound exam for Models 1 and 2 and decreasing the favourability of models incorporating telerobotic ultrasound.

While the absolute cost per ultrasound exam for each model will likely differ between countries, relative differences between each of the models presented in this manuscript may provide valuable information for international health systems and payers. For countries without a certain proportion of the population eligible for publicly funded medical transportation (as was included in this study for Canadian First Nations persons), the scenario of 0% of the population eligible for publicly funded medical transportation may be most informative. With 0% of the population eligible for publicly funded medical transportation, Model 4 (patient travel required for all exams) has the lowest average cost per ultrasound exam ($121 CAD; $90 USD), followed by Model 1 (telerobotic ultrasound—$238 CAD; $177 USD), with Model 2 (telerobotic ultrasound and an itinerant sonographer) and Model 3 (itinerant sonographer) being higher cost from a payer perspective. From a societal perspective, Model 2 (telerobotic ultrasound and an itinerant sonographer) is lowest cost ($358 CAD; $267 USD), followed by Model 3 (itinerant sonographer—$461 CAD; $343 USD), with Model 4 (requiring patient travel for all exams) the highest cost.

This economic analysis does not directly address the issue of whether it is financially sustainable for radiology practices to deploy telerobotic ultrasound systems in rural and remote communities if the radiology practice itself is responsible for purchasing the equipment. However, key considerations for radiology practices to consider are whether the volume of exams in the community is sufficient to justify the cost of purchasing or leasing a telerobotic ultrasound system, and whether technical component reimbursements are sufficient to absorb the additional salary for a patient-site assistant in the remote community and the increased sonographer time required to complete telerobotic ultrasound exams. The capital costs of a telerobotic ultrasound system may decrease considerably in the future as technology advances and more systems are deployed. This has been our experience with the use of remote presence technology for virtual acute care in remote communities.[21,22] Additionally, as telerobotic technology evolves, the proportion of exams which are non-diagnostic (leading to a recommendation for a repeat conventional exam) may decrease, minimizing the number of repeated exams and lowering costs for models incorporating telerobotic ultrasound.

There are a few limitations to this study. The base case analysis is based on a specific community in northern Saskatchewan, Canada with Saskatchewan-specific current costs, and results may not be generalizable to all communities. In the case of labor costs, for example, some healthcare salaries in Canada are lower than in the United States and some European countries, but are higher than other European and Asian countries.[23] Additionally, the Canadian context of medical transportation costs being covered by a public payer for a portion of the population may not be applicable to other countries. Our cost estimates were based on a specific telerobotic ultrasound system, and other types of telerobotic ultrasound systems may have different costs. Second, there is considerable uncertainty in some model parameters and cost estimates, which in some cases were based on personal communication and our local experience developing telerobotic ultrasound clinics in three northern Saskatchewan communities. Some of these parameters, such as the proportion of exams which are urgent or emergent, may vary based on local clinical practice and may not be applicable to other practice settings. Third, assumptions on diagnostic performance and the proportion of telerobotic ultrasound exams for which a conventional ultrasound exam is recommended is dependent on radiologist reporting practices, either increasing or decreasing the average cost per ultrasound exam for Models 1 and 2. Based on two recent studies, this study considered equivalent diagnostic performance between telerobotic and conventional methods among ultrasound exams for which the radiologist does not recommend that the exam be repeated conventionally.[6,7] However, even in cases where radiologists may not recommend a repeat exam, the exam may be of lower quality and findings could potentially be missed that would otherwise be detected using conventional ultrasound. Further studies should assess any differences in health outcomes between patients assessed using telerobotic versus conventional ultrasound, and these data could be then used as inputs for an updated economic analysis.

Conclusion

While many benefits and limitations of telerobotic ultrasound have previously been described in the literature, this study provides an additional perspective to inform ultrasound service delivery in rural and remote communities. A service delivery model which brought ultrasound services closer to patients' own communities through telerobotic ultrasound combined with an itinerant sonographer service was the lowest cost option from publicly funded healthcare payer and societal perspectives for various communities. The process of determining the most appropriate model of ultrasound service delivery should be made in the context of each unique community and in collaboration with community leaders, with consideration given to community population size, distance to the nearest ultrasound facility, and available health human resources. The applications of telerobotic ultrasound in low-resource, underserved populations may have important implications in narrowing the gap of equity in accessing essential diagnostic services such as ultrasound at a global level.

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