

IMPROVING ACCESS TO ULTRASOUND IMAGING IN
NORTHERN, REMOTE COMMUNITIES

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By

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ABSTRACT

Access to healthcare services—including access to medical imaging—is an important determinant of health outcomes. This thesis aims to improve understanding of and address gaps in access to ultrasound imaging for patients in northern, remote communities, and advance a novel ultrasound technology with the ultimate goal of improving patient care and health outcomes.

This thesis first brings greater understanding of patients' perceptions of access and factors which shape access to ultrasound imaging in northern, remote communities in Saskatchewan, Canada. A qualitative study was performed using interpretive description as a methodological approach and a multi-dimensional conceptualization of access to care as a theoretical framework. The study identified barriers which patients in northern, remote communities face in accessing ultrasound imaging, and demonstrated that geographic remoteness from imaging facilities was a central barrier.

To determine whether disparities in *access* to ultrasound imaging resulted in disparities in *utilization* of ultrasound services, two population-based studies assessed the association between sociodemographic and geographic factors and obstetrical and non-obstetrical ultrasound utilization in Saskatchewan. In the first study investigating obstetrical ultrasound utilization, multivariate logistic regression analysis demonstrated that women living in rural areas, remote areas, and low income neighbourhoods, as well as status First Nations women, were less likely to have a second trimester ultrasound, an important aspect of prenatal care. In a second study investigating non-obstetrical ultrasound utilization across the entire provincial population, multivariate Poisson regression analysis similarly demonstrated lower rates of non-obstetrical ultrasound utilization among individuals living in rural and remote areas, individuals residing in low income neighbourhoods, and status First Nations persons.

To address the barriers which patients in northern, remote communities face in accessing ultrasound imaging and to minimize disparities in ultrasound imaging utilization as identified in previous studies in this thesis, telerobotic ultrasound technology was investigated as a solution to improve access to ultrasound imaging. Using this technology, radiologists and sonographers could remotely manipulate an ultrasound probe via a robotic arm, thereby remotely performing an ultrasound exam while patients remained in their home community. A clinical trial comparing

conventional and telerobotic ultrasound approaches was undertaken, validating this technology for obstetrical ultrasound imaging.

To determine the feasibility of using telerobotic technology to establish an ultrasound service delivery model to remotely provide diagnostic ultrasound exams in underserved communities, pilot telerobotic ultrasound clinics were developed in three northern, remote communities. Telerobotic ultrasound exams were sufficient for diagnosis in the majority of cases, minimizing travel or reducing wait times for these patients. This technology was subsequently evaluated during a COVID-19 outbreak in northern Saskatchewan, demonstrating the potential of this technology to provide critical ultrasound services to an underserved northern population and minimize health inequities during the COVID-19 pandemic.

An economic evaluation was performed to compare a service delivery model using telerobotic ultrasound technology to alternative service delivery models. Telerobotic ultrasound combined with an itinerant sonographer service was found to be the lowest cost option from both a publicly funded healthcare payer perspective and a societal perspective for many northern, remote communities.

This thesis provides key insights for health system leaders seeking improved understanding and novel solutions to improve access to ultrasound imaging in northern, remote communities. Findings suggest that telerobotic ultrasound is a viable solution to improve access to ultrasound imaging and reduce costs associated with ultrasound service delivery. Evidence in this thesis may be used to help improve ultrasound services and health equity for patients in underserved northern, remote communities. Continued respectful collaboration with northern, remote, Indigenous peoples and communities will be a critical aspect to ensure that ultrasound services meet community needs.

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LIST OF ABBREVIATIONS

2D	2-dimensional
3D	3-dimensional
AI	artificial intelligence
aIRR	adjusted incidence rate ratio
aOR	adjusted odds ratio
CCI	Charlson Comorbidity Index
CI	confidence interval
CLXT	combined laboratory and X-ray technologist
COVID-19	coronavirus disease 2019
CSD	census subdivision
CT	computed tomography
DOF	degrees-of-freedom
FAST	focused assessment with sonography for trauma
GEE	generalized estimating equation
ICD	International Classification of Diseases
IRR	incidence rate ratio
LMP	last menstrual period
MRI	magnetic resonance imaging
MSB	Medical Services Branch (Saskatchewan Ministry of Health)
OR	odds ratio
PACS	picture archiving and communication system
RIS	radiology information system
SD	standard deviation

CHAPTER 1

INTRODUCTION

Ultrasound imaging is critical for many medical diagnoses. It is used for making diagnoses of conditions which are potentially life threatening if not appropriately managed, such as ectopic pregnancy or acute appendicitis, and is a component of routine management of pregnancies, as in the case of ultrasound exams for fetal dating or screening for anomalies. Ultrasound is a preferred imaging modality for many clinical indications as it is widely available in most large communities, offers increased diagnostic confidence over other imaging modalities for specific diagnoses, is inexpensive relative to advanced imaging modalities, and is not associated with ionizing radiation.¹

Ultrasound imaging is operator-dependent and skilled radiologists and/or sonographers are required to adequately assess all required anatomy as part of a diagnostic ultrasound exam.² As a result of the need for skilled radiologists and/or sonographers to obtain diagnostic images, ultrasound imaging is not available in many smaller communities. Difficulty recruiting and retaining sonographers to provide ultrasound services in these smaller communities and the small patient population and low volume of exams performed in some of these communities result in a lack of ultrasound services in many communities around the world.^{1,3}

The lack of ultrasound services in smaller communities is particularly challenging for northern and remote communities in Canada, where the nearest ultrasound centre or hospital with ultrasound services may be hundreds of kilometres away.³ In Saskatchewan and much of Canada, the large geographic region over which the population resides creates challenges in the delivery of medical imaging services, including ultrasound imaging. A large proportion of the population in Canadian northern, remote communities is Indigenous. Indigenous peoples are disproportionately faced with gaps in access to healthcare and disparities in health outcomes. While these challenges are multifactorial, access to healthcare services is an important determinant of health outcomes.⁴

This thesis aims to improve understanding of and address gaps in access to ultrasound imaging for patients in northern, remote communities, and to advance a novel ultrasound technology—telerobotic ultrasound—with the ultimate goal of improving patient care and health outcomes. This thesis encompasses eight manuscripts (Appendix), organized as follows.

Following this introductory chapter, Chapter 2 first situates this thesis within a discussion of the geographical, social, and cultural dimensions of northern, remote communities in Saskatchewan—the setting of this research. I discuss the challenges and opportunities in providing healthcare services, including medical imaging and specifically ultrasound imaging, in northern Saskatchewan. I then discuss current literature surrounding telerobotic ultrasound as a potential solution to improve access to ultrasound imaging.

Chapter 3 presents a qualitative study exploring northern, remote community members' perceptions of access and factors which shape access to ultrasound imaging services in their communities. Chapters 4 and 5 present two population-based studies which explore sociodemographic and geographic factors associated with obstetrical and non-obstetrical ultrasound imaging utilization, respectively. Together, the studies in Chapters 3 through 5 help inform efforts to improve access to ultrasound imaging in northern, remote communities.

Informed by research presented in Chapters 3 through 5, Chapters 6 through 9 evaluate and advance telerobotic ultrasound technology as a potential solution to improve access to imaging. This technology allows radiologists and sonographers to remotely perform ultrasound exams via a robotic arm. Chapter 6 presents results from a clinical trial validating a telerobotic approach to perform obstetrical ultrasound exams, which builds off of my prior work validating a telerobotic approach for abdominal ultrasound exams.⁵

Chapter 7 describes the development, implementation, and evaluation of telerobotic ultrasound clinics in three northern, remote communities in Saskatchewan, the first of their kind in North America. This chapter describes clinical workflows which were developed and evaluates this model of care in the domains of diagnostic assessment, patient experience, and health system and radiology practice integration.

Our world was disrupted by the COVID-19 pandemic in early 2020, and due to urgent healthcare needs during the pandemic, our team was called on to provide critical ultrasound services using telerobotic ultrasound in La Loche, a community which became the epicentre of the first wave of the COVID-19 pandemic in Saskatchewan. Chapter 8 describes the rapid development of a telerobotic ultrasound clinic to provide critical ultrasound services in La Loche during this unprecedented time, an evaluation of the provision of obstetrical ultrasound services using telerobotic ultrasound, and considerations for deploying this technology during the COVID-19 pandemic.

Chapter 9 considers the economic implications of this technology in our health system by presenting an economic evaluation of the provision of ultrasound services using a telerobotic ultrasound system compared to other models of providing ultrasound services in northern, remote communities.

Finally, Chapter 10 provides concluding remarks, implications of this thesis for healthcare systems, and future research directions.

This thesis makes several important contributions to diagnostic radiology, virtual care and remote presence medicine, and health services research. Research presented in this thesis brings increased understanding and attention to the unique challenges and needs of patients in northern, remote communities in accessing medical imaging, an area which has been underexplored in the diagnostic radiology literature. The use of a qualitative methodology in Chapter 3—a methodology rarely used in the diagnostic radiology literature—demonstrates how this methodology may be employed to explore health disparities in medical imaging and inform the development of solutions to better meet the imaging needs of populations. This research bridges diagnostic radiology and remote presence medicine by investigating telerobotic ultrasound in the first real-world clinical exploration of this technology in North America. This thesis also helps advance virtual care and remote presence medicine beyond audio and video consultation into a new domain: equipping physicians and sonographers with the ability to perform imaging exams via a robotic arm.

Results from these studies provide health system leaders with important insights which can be used to improve ultrasound services in northern, remote communities. Based on our team's experience establishing three telerobotic ultrasound clinics in Saskatchewan, this thesis identifies operational challenges and potential solutions which health system leaders may encounter when developing telerobotic ultrasound clinics. The use of this technology during the COVID-19 pandemic to help meet urgent healthcare needs provides evidence regarding the significant potential of this technology and the impact of this research for communities. The economic evaluation presented in this work provides information to assist health system leaders in making evidence-informed decisions.

Ultimately, this thesis provides evidence which may be used to help improve access to ultrasound imaging and improve health equity for patients in northern, remote communities.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW*

Significant health disparities exist between northern and non-northern populations and between Indigenous and non-Indigenous populations in Saskatchewan and Canada.^{6,7} The factors influencing health outcomes are multifactorial and include access to healthcare services and a broad range of social determinants of health.^{4,8,9} Motivated by health disparities which exist, I will begin this chapter by situating my thesis within a discussion about the geographical, social, and cultural dimensions of northern Saskatchewan, which is the setting of this research. I will discuss some of the challenges and opportunities related to the provision of healthcare services, followed by a discussion of the provision of medical imaging services—and more specifically ultrasound services—in northern Saskatchewan and more broadly in northern Canada. I will then discuss telerobotic ultrasound, a technology which holds significant potential to increase access to ultrasound imaging in northern, remote communities. I will review the development of telerobotic ultrasound systems, clinical applications of telerobotic ultrasound, and early work assessing the use of telerobotic ultrasound in clinical settings, and suggest what additional research is required to support its development and implementation in health systems in Saskatchewan and beyond.

2.1 Health and healthcare in Saskatchewan's northern, remote communities

2.1.1 Population demographics

The region often referred to as northern Saskatchewan (here defined as Census Division No. 18, roughly equivalent to the region served by the Athabasca Health Authority and the former Keewatin Yatthé and Mamawetan Churchill River Regional Health Authorities), comprises a large proportion of the province of Saskatchewan—approximately 46% of the provincial surface area (Figure 2.1).^{10,11} Despite its large land area, just over 37,000 people, or approximately 3.4% of the province's population, reside in this region.¹¹ There are approximately 70 communities in northern Saskatchewan.

* A portion of this chapter has been published as:

Adams SJ, Burbridge B, Obaid H, Stoneham G, Babyn P, Mendez I. Telerobotic sonography for remote diagnostic imaging: narrative review of current developments and clinical applications. *J Ultrasound Med.* 2021;40(7):1287-1306. doi:10.1002/jum.15525.

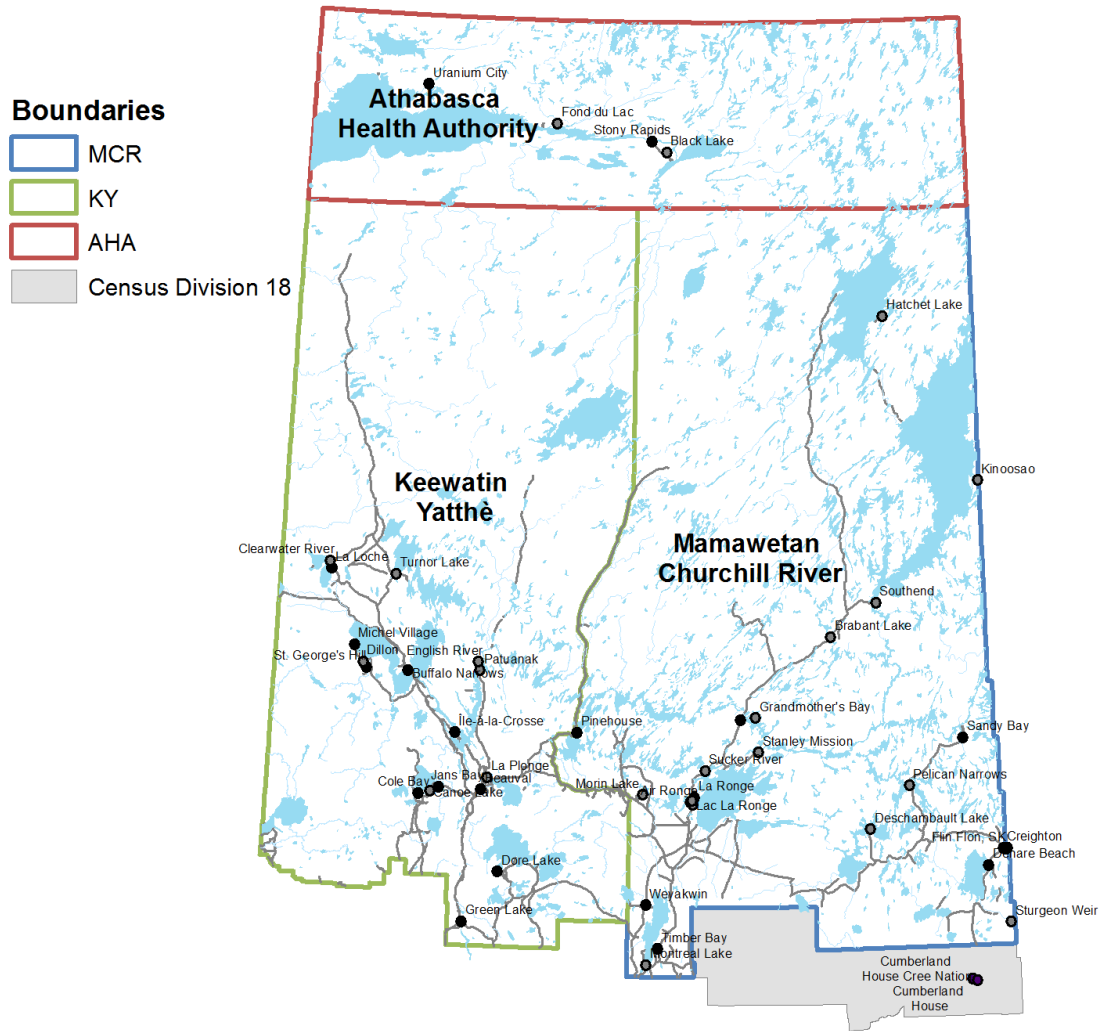


Figure 2.1. Map of northern Saskatchewan, Canada. Northern Saskatchewan, defined for the purposes of this thesis as Census Division No. 18, is roughly equivalent to the region served by the Athabasca Health Authority and the former Keewatin Yatthé and Mamawetan Churchill River Regional Health Authorities. Reproduced with permission.¹⁰

The population density per square kilometre in northern Saskatchewan is 0.1, compared to 1.9 for the province as a whole.¹¹ This substantial geographic dispersion of the population creates challenges for the provision of healthcare services.

Over 87% of the population in northern Saskatchewan is Indigenous, of whom approximately 79% are First Nations and 20% are Métis.¹¹ Across northern Saskatchewan, 41% of the population reports having an Indigenous language as their mother tongue.¹¹ Cree and Dene are the most common Indigenous languages in northern Saskatchewan.¹¹ As discussed in section

2.1.3, Indigenous peoples face many barriers, historical and current, in achieving optimal health outcomes.

The region has unique population age demographics, with approximately 93% of the population less than 65 years old, compared to 84% for the province as a whole.¹¹ The younger population of northern Saskatchewan relates to a birth rate which is approximately two-fold greater than the total population of Saskatchewan.¹² These population demographics make the provision of prenatal care, including obstetrical ultrasound, particularly important for northern Saskatchewan.

2.1.2 Social determinants of health

Lower rates of education, unemployment, lower income, poverty, and lack of suitable housing are among the many realities faced by northern Saskatchewan people.⁹ These factors are recognized as important social determinants of health.⁸ Approximately 43% of individuals age 25-64 years in northern Saskatchewan do not hold a certificate, diploma, or degree, approximately 3.5-times the proportion among individuals across all of Saskatchewan (12%).¹¹ The unemployment rate is significantly higher among northern populations at 23.8%, compared to 7.1% for Saskatchewan.¹¹ A lack of employment opportunities in many northern communities is a key contributing factor to the high unemployment rate. This translates into a lower median income for the population, with the median after-tax income of northern Saskatchewan residents 15 years and older only 57% of the provincial median.¹¹ Availability of suitable housing and crowding are also continuing challenges in many communities, with 4.8-11.4 times the rate of crowding compared to the rest of the province.^{9,11} These social determinants of health, including lower income levels, lower employment levels, lower education levels, and lack of suitable housing, have a substantial impact on the health of northern people.⁹

2.1.3 Indigenous health

The previously described social determinants of health are compounded by cultural factors which continue to adversely impact the health of Indigenous peoples in northern Saskatchewan. The health of Indigenous peoples must be understood in the context of a legacy of colonisation and colonialism.¹³⁻¹⁵ Policies which displaced Indigenous peoples from traditional lands and confined Indigenous peoples to reserves, disrupted Indigenous forms of government, and suppressed Indigenous languages and cultures created economic, political, and social inequalities among Indigenous peoples in Canada.^{8,13} Many of these inequalities are reflected in

conditions which continue to compromise health outcomes in northern Saskatchewan Indigenous communities today, such as lower income, lower employment levels, and inadequate housing.

The health of Indigenous peoples must also be understood in the context of traditional Indigenous practices of health and healing. The concept of holistic health is central to Indigenous health and wellness, which operates at the personal level as “health and wellness in body, mind, heart, and spirit”; at the family level as “mutual support of each other” and at the community level as “leadership committed to whole health, empowerment, sensitivity to interrelatedness of past, present, and future possibilities, and connected between cultures.”^{15,16} Among many Indigenous cultures, the medicine wheel represents the importance of balance between physical, emotional, mental, and spiritual health. Indigenous cultures view illness as imbalance in any one of these four aspects.¹⁵ A commitment to the Indigenous concept of holistic health is reflected, for example, in the Athabasca Health Authority’s mission, as a health authority “Where comprehensive health services will be provided in an integrated and holistic manner to support, nurture and restore physical, mental, spiritual and emotional health.”¹⁷

Indigenous peoples continue to face racism, discrimination, and stereotyping within the Canadian healthcare system.¹⁸ Healthcare services are felt by some to contradict Indigenous values, interests and priorities, and devalue Indigenous health and wellness.¹⁹ As a result, some Indigenous peoples may be reluctant to access healthcare services.¹⁸ There have been multiple calls for cultural safety training among healthcare staff to improve care and minimize racism in the healthcare system^{18,19} and create a healthcare system which builds upon the strengths of Indigenous communities.¹⁹ Thus, efforts to improve access to healthcare services—including ultrasound services—must consider the holistic health needs of Indigenous peoples and build upon the strengths of Indigenous communities through respectful collaboration.

2.1.4 Health status

The interaction between cultural and historical factors which are specific to Indigenous peoples as well as other social determinants of health contribute to health disparities between northern Saskatchewan residents and the general Canadian population. The age-standardized all-cause mortality rate in northern Saskatchewan is 943 per 100,000 individuals, compared to 790 per 100,000 individuals for Saskatchewan.⁶ Across all ages and across both sexes, mortality rates are higher in northern Saskatchewan compared to the rest of the province, with injuries—

including intentional self-harm, motor vehicle accidents, assault, and accidental poisonings—the leading causes of death.⁶

Indigenous peoples across Canada have higher mortality rates and shorter life expectancy. Based on available data from the Canadian Census Health and Environment Cohorts, life expectancy at age 1 was approximately 9 to 10 years shorter for First Nations people than for non-Indigenous people, and 4.5 to 5 years shorter for Métis than for non-Indigenous people.⁷ Indigenous peoples in Canada also have a higher rate of obstetrical complications relative to non-Indigenous individuals, with multiple studies demonstrating higher rates of stillbirths among Indigenous individuals compared to non-Indigenous individuals.^{20–22}

2.1.5 Jurisdiction of health services

Provision of healthcare services in northern Saskatchewan is complex, with federal, provincial, and First Nations jurisdictions. With the establishment of a provincial health authority in 2017, the Saskatchewan Health Authority became responsible for healthcare services previously provided by the Keewatin Yatthé and Mamawetan Churchill River Regional Health Authorities. The Athabasca Health Authority, which serves the most northern part of the province, continues as a unique partnership between the federal and provincial governments and First Nations. Formed in 1994, this health authority was the first integrated federal, provincial and First Nations health services organization in Canada.²³ Multiple First Nations in Saskatchewan, including the Peter Ballantyne Cree Nation and Lac La Ronge Indian Band, are responsible for the administration of health services following transfer agreements with the federal government.¹⁰

A distinctions-based approach is helpful to understand healthcare services across Indigenous peoples. Only status First Nations and Inuit persons are eligible for the Non-Insured Health Benefits program administered by the federal government, excluding Métis people and other individuals who are not recognized as status First Nations persons under the *Indian Act*. While Métis people are eligible for provincially available health services, often these health services do not recognize their unique cultural needs.⁴ While transfer of responsibility for the administration of healthcare services to First Nations provides First Nations with a greater degree of autonomy and self-determination, in some cases transfer agreements have resulted in inequitable distribution between provinces and territories and between communities.⁴

2.1.6 Provision of health services

The provision of healthcare services in northern, remote communities poses a number of unique challenges. Geographic dispersion of the population resulting in a large number of small communities separated by vast distances, difficulty recruiting healthcare personnel to work in northern and remote communities, the need for increased travel and transport for healthcare services, and higher costs related to the provision of care in northern, remote communities are among the challenges faced.^{24–26}

In Saskatchewan's northern communities, physician services are provided by Northern Medical Services, a division of the University of Saskatchewan's Department of Academic Family Medicine.²⁷ Family physicians are based at five sites, including Île-à-la-Crosse, La Loche, Stony Rapids, La Ronge, and Pelican Narrows, with physician services at three of the sites provided by itinerant physicians. Family physicians also have clinic days at outpost nursing stations on a regular basis. Specialist clinics are intermittently held in these northern communities.²⁷ The limited number of patients which can be seen by physicians and the limited number of clinics per year (often only three to four per year) pose substantial challenges for residents accessing primary and specialist care in northern communities.²⁸ Indeed, a 2018 report from the Saskatchewan Health Authority describing needs and priorities for Indigenous health in Saskatchewan identified the need for better access to health services, particularly in the north.²⁹ As will be discussed in section 2.1.8, it is important these efforts extend to medical imaging, which is limited in many northern communities.

2.1.7 Telehealth

Technologies encompassing telehealth, including remote presence systems and virtual care, have been evaluated and implemented as solutions to help improve access to care in rural and remote communities in Saskatchewan.^{30–35} Conventional telehealth, allowing patients to connect with physicians or other healthcare providers at specific times via videoconferencing at specific facilities across Saskatchewan, is well established in Saskatchewan, with 385 telehealth sites across 137 communities.³⁰

Beyond traditional telehealth consultations, the use of remote presence robots has emerged in Saskatchewan, offering flexibility in scheduling, remote manoeuvrability to see patients at the bedside, and peripheral devices including stethoscopes and otoscopes to assist physicians in conducting a physical exam.³³ The use of an RP-7i remote presence robot (InTouch

Health, Santa Barbara, CA) in northern Saskatchewan for consultation with a pediatric intensivist reduced the need for pediatric inter-facility transfer, and enabled patients to be transferred to a regional hospital when appropriate.³¹ This technology has also been used for physical therapy consultations.³²

Some of the benefits of telehealth and virtual care have included increased access to specialists, more timely care, increased patient convenience, reduced time away from home and work for medical appointments, and reduced costs related to travel to another community for care.^{30,36,37} Remote presence systems have been viewed as supporting decolonization of health systems in Indigenous communities, as they enable direct connection between patients and health care providers while patients stay in their home community, support partnerships in developing management plans, and support self-determination by valuing patients' priorities.³³ Telehealth has been viewed as a technology which enables cultural integrity, traditional values, and Indigenous languages to be respected.³⁰

However, telehealth with traditional videoconferencing poses some challenges in the clinical setting: scheduling telehealth appointments lacks flexibility, there is limited space for telehealth consultations, clinical support for telehealth consultations is limited, there are often challenges in recruiting local telehealth coordinators, and policy and legislation must be updated for new virtual consultation services that are mobile.^{30,36} Some of these challenges may be addressed through the use of remote presence robots, providing increased flexibility for urgent care and enhanced capabilities for patient assessment.³³ Additional recommendations to allow telehealth to better serve patients in northern Saskatchewan have included advocating for increased bandwidth availability in northern communities, providing increased financial support to rural and remote clinics, and ensuring physicians are equally compensated for telehealth visits as compared to in-person visits.³⁰ Benefits and challenges associated with telehealth solutions which have been used to improve access to physician services in northern, remote communities are important considerations to inform the provision of medical imaging services in these communities. Additionally, the COVID-19 pandemic has resulted in increased experience in using virtual care and a greater health system focus on addressing health system needs with virtual care.³⁸

2.1.8 Medical imaging

Medical imaging is a core component of modern healthcare services. Imaging has applications across screening, diagnosis, assessing prognosis, and monitoring treatment response, with a demonstrated impact on improving health outcomes.^{39,40} Core imaging modalities include radiography (X-ray imaging) and ultrasound imaging and advanced imaging modalities include computed tomography (CT) and magnetic resonance imaging (MRI), among others. It has been estimated that 80-90% of imaging needs in developing countries can be met with radiography and ultrasound imaging alone.⁴¹ Imaging has become an increasingly important aspect of patient care, and the volume of imaging studies performed continues to increase.⁴²

Ultrasound imaging, the focus of this thesis, is routinely employed to assist in management of a wide variety of pathologies across multiple organ systems, and is particularly suited to abdominal, pelvic, obstetrical, breast, musculoskeletal, and soft tissue imaging. Ultrasound imaging is considered one of the most operator-dependent imaging modalities, and experts are required to provide quality diagnostic exams.⁴³ In Saskatchewan, most general diagnostic ultrasound exams are performed by sonographers (ultrasound technologists) under the supervision of a radiologist. Sonographers manipulate an ultrasound transducer which generates and transmits high frequency sound waves through tissues of interest. Images are generated based on analysis of sound waves which are reflected and detected by the ultrasound transducer.¹ The resultant images are presented on a digital monitor allowing the sonographer to dynamically view the images as they are being acquired. Images can be saved and stored on a picture archiving and communication system (PACS) for subsequent interpretation by a radiologist.

Teleradiology—the interpretation of images on PACS by radiologists remotely—has revolutionized timely access to radiologists, with radiologists now being able to read imaging exams performed at multiple locations.⁴⁴ While teleradiology creates the potential for radiologists to read images from northern and remote communities with little or no disruption in workflow, capacity for imaging exams to be performed in northern and remote communities remains limited, partly due to resource constraints limiting the acquisition of imaging equipment and the need for trained technologists to acquire the images.

Despite being a core imaging modality, ultrasound imaging is not regularly available in many northern, remote communities in Saskatchewan. This can be attributed to difficulty recruiting and retaining sonographers in these communities and the low-volume of ultrasound

exams required in many smaller communities making it difficult to employ full-time sonographers in these communities. Ultrasound services in northern Saskatchewan are provided by the University of Saskatchewan's Northern Medical Services with an itinerant sonographer flying to Stony Rapids, La Loche, and Île-à-la-Crosse generally on a monthly basis. On all days other than the generally one day per month in which the sonographer is in the community, ultrasound imaging is not locally available, and patients requiring urgent imaging must travel or be transported to another community for imaging. Figure 2.2 maps the locations of ultrasound facilities which offer ultrasound services at least 100 days per year. As can be seen from the figure, vast distances separate many patients from centres with ultrasound imaging services.

While there are multiple conceptual frameworks describing access to healthcare services in general,⁴⁵⁻⁴⁸ there is limited literature regarding how access to ultrasound imaging is conceptualized, particularly in northern, remote communities in Canada. Additionally, limited data exists regarding how remoteness impacts ultrasound imaging utilization, and there have been few strategies to improve access to ultrasound for northern and remote Saskatchewan communities beyond recruitment of sonographers and use of itinerant sonographers.

To inform the provision of ultrasound imaging services in northern, remote communities, many lessons can be learned from the provision of other imaging modalities. Radiography is the highest volume imaging modality in most practice settings, and is the most common imaging modality available in many northern and remote communities. However, recruiting and retaining qualified technologists is a persistent challenge in northern and remote communities. Many rural and remote communities in Saskatchewan are served by combined laboratory and X-ray technologists (CLXTs). Saskatchewan's CLXT program developed in the 1940s as a result of the need for both skill sets in many rural Saskatchewan hospitals and the low volume of work at each hospital.⁴⁹ In other communities, as radiography is a less operator-dependent modality compared to ultrasound, a wide range of healthcare staff are responsible for acquiring X-rays. In some northern and remote communities in Canada's territories, primary care nurses or housekeeping staff may acquire X-ray images, with training on an ad hoc basis.³ Concerns regarding quality and the lack of an imaging quality assurance program can arise, with many northern and remote communities having no administrative leaders dedicated to imaging.³ Northern communities which have been able to secure imaging equipment and sufficient staff to operate the equipment have found great benefits. The first CT scanner in Nunavut was installed

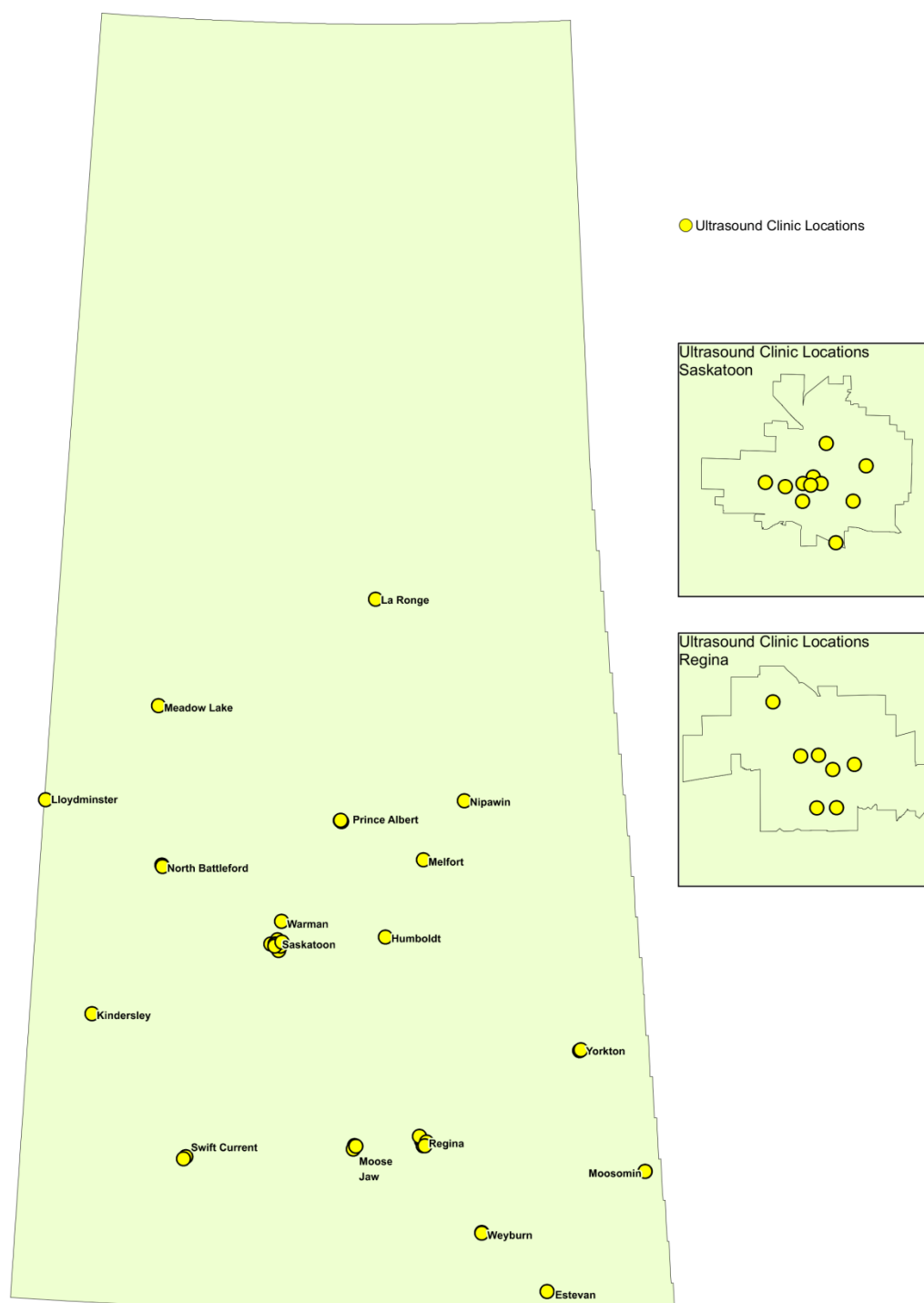


Figure 2.2. Ultrasound facilities which offer ultrasound services at least 100 days per year in Saskatchewan.

in Qikiqtani General Hospital in Iqaluit in 2014. Prior to the CT scanner being installed, over 400 patients were transported annually to Ottawa for CT imaging, with an average cost of \$2,600 per patient for accommodation and other expenses and, for emergency cases, approximately \$25,000 for a round-trip flight, crew, and in some cases nurses and physicians as escorts. While data following installation of the CT scanner is limited, anecdotal findings include reduced travel for patients, reduced wait times, and increased diagnostic confidence among physicians as a result of having CT imaging locally available.⁵⁰ This suggests that solutions which bring other imaging modalities, including ultrasound imaging, closer to patients' home communities may also be of substantial benefit.

2.2 Telerobotic ultrasound

The previous section provided context into the unique health needs of residents of northern, remote communities. It emphasized the structural health inequities between Indigenous and non-Indigenous peoples and the challenges associated with providing care in northern, remote communities. It also identified the benefits of virtual care technologies and the potential benefits of bringing imaging services closer to patients' home communities. In response to these challenges and the need to explore new healthcare delivery solutions in partnership with Indigenous communities, the second part of this chapter explores the use of telerobotic ultrasound as a potential technological solution to help improve access to ultrasound imaging and improve health equity in northern, remote communities.

Limited access to ultrasound imaging in many communities around the world has motivated efforts to harness advances in robotics and telecommunications to develop telerobotic ultrasound systems—ultrasound systems that allow expert sonographers to manipulate an ultrasound probe in real-time from a distant location, thereby allowing sonographers to remotely perform a diagnostic ultrasound examination.⁵ Following more than 20 years of research and development, the first generation of telerobotic ultrasound systems are now commercially available,^{51–53} promising greater access to ultrasound for patients in communities which would otherwise not have access to ultrasound. This section traces the development of telerobotic ultrasound systems and reviews published studies evaluating the feasibility and diagnostic accuracy of telerobotic ultrasound. The emerging use of telerobotic ultrasound in clinical settings

and opportunities for future research, development, and clinical implementation as telerobotic ultrasound advances is also discussed.

2.2.1 Telerobotic ultrasound systems

2.2.1.1 General concepts

To remotely perform an ultrasound examination, telerobotic ultrasound systems should ideally provide a means for sonographers to remotely manipulate an ultrasound probe, view the ultrasound images on the ultrasound unit interface, remotely control ultrasound unit settings and functions such as gain and depth, and provide a means for the sonographer and patient to communicate. A typical telerobotic ultrasound system is presented in Figure 2.3. At the patient-site, a 3-degrees-of-freedom (DOF) manipulator (robotic arm) holds the scanning ultrasound probe. An assistant at the patient-site holds the frame of the 3-DOF manipulator.^{5,54} At the sonographer-site, the sonographer's movements of a mock probe are directly replicated by the scanning ultrasound probe at the patient-site via the 3-DOF manipulator. Through the ultrasound unit interface transmitted to the sonographer-site, the sonographer can view all acquired images and control ultrasound unit settings and functions. A standard videoconferencing system provides a means for the sonographer, patient, and patient-site assistant to communicate.^{5,54}

As telerobotic ultrasound systems are “master-slave” systems, the remote manipulator (end-effector) to which the ultrasound probe is attached is controlled by sending position commands from the sonographer-site to the patient-site.⁵⁵ Control of the movements of the end-effector is achieved using various technologies, including a mock ultrasound probe allowing sonographers to use the same movements as when conventionally scanning a patient^{5,54} or a computer mouse and graphical user interface to indicate the desired movement or position of the ultrasound probe.⁵⁶ An important feature of telerobotic ultrasound systems is the number of DOFs of the robotic manipulator. A greater number of DOFs allows the robotic manipulator to be more dexterous and achieve the basic movements required to replicate ultrasound scanning to a greater extent.⁵⁵

Telerobotic ultrasound systems have been categorized as having applications for short-distance and long-distance operation.⁵⁵ Long-distance telerobotic ultrasound systems enable sonographers to perform ultrasound exams where significant geographical distances separate the patient and sonographer, for example between urban and rural and remote communities. Short-

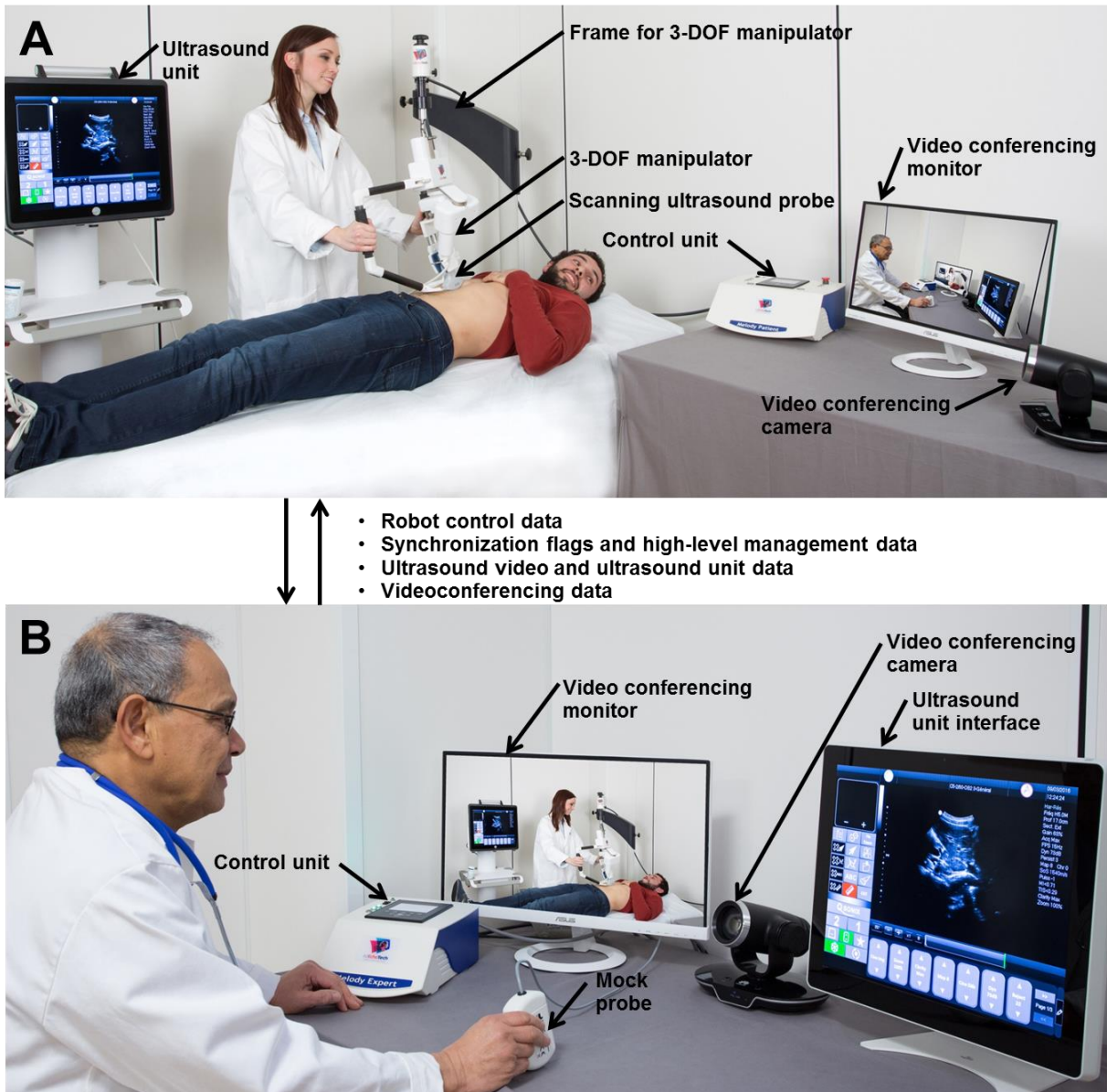


Figure 2.3. Telerobotic ultrasound system at the patient and sonographer sites. (a) At the patient-site, a 3-degrees-of-freedom (DOF) manipulator (robotic arm) holds the scanning ultrasound probe. An assistant at the patient-site holds the frame of the 3-DOF manipulator and adjusts the frame for the manipulator to control sliding and compression of the probe as instructed by the sonographer. (b) At the sonographer-site, a sonographer or sonologist remotely controls movements of the scanning ultrasound probe (including rocking, rotation, and tilting) by manipulating a mock probe. The sonographer can view all ultrasound images and control ultrasound unit settings and functions through the ultrasound unit interface transmitted to the sonographer-site. A standard videoconferencing system provides a means for the sonographer, patient, and patient-site assistant to communicate. Data transmitted between the patient-site and the sonographer-site include robot control data, synchronization flags and high-level management data, ultrasound video and ultrasound unit data, and videoconferencing data.⁵⁴ Images courtesy of Société AdEchoTech (Naveil, France); used with permission.

distance telerobotic ultrasound systems enable sonographers to manipulate an ultrasound probe even when they are in the same room as the patient. Potential applications of short-distance telerobotic ultrasound systems—beyond the scope of this review—include integration into robotic surgical systems for image guidance,^{57,58} image guidance during robotic brachytherapy seed placement,⁵⁸ or robotic positioning of an ultrasound probe when performing an ultrasound-guided procedure.⁵⁹

2.2.1.2 Telecommunications requirements

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

- (1) robot control data, which are bidirectional data sent to/from (i) the sonographer-site to the patient-site, enabling movements of the mock probe to be reproduced by the scanning probe at the patient-site and (ii) the patient-site to the sonographer-site, providing haptic feedback;
- (2) synchronization flags and high-level management data, which are small bidirectional byte packets used to synchronize the probe manipulator at the patient-site and mock probe at the sonographer-site, reset the system, and control the sampling frequency for robot control data;
- (3) ultrasound video and ultrasound unit data, transmitting ultrasound video from the ultrasound unit located at the patient-site to the sonographer-site, and control of ultrasound unit settings and functions from the sonographer-site back to the patient-site; and
- (4) videoconferencing data, allowing the patient, sonographer, and patient-site assistant to view and communicate with each other.⁵⁵

A primary concern in telerobotic ultrasound systems is latency, the time delay between the sonographer moving the mock probe, corresponding movement of the robotic arm, and the resulting ultrasound image being returned to the sonographer. There is an inherent delay in data transmission secondary to the time needed for data to travel over a distance, as well as latency intrinsic to the computer network and communications architecture.⁶⁰ The latter is more difficult

to predict, as data packets transmitted through a communications network are dynamically allocated based on network load and routing policies, resulting in latency and jitter (variation).^{55,60} Adding to the complexity, congestion may occur if the number of data packets is in excess of the bandwidth which is available, resulting in increased latency.⁵⁵

Ultrasound video data require more bandwidth than robot control data, and available bandwidth must be shared between these data types. Temporal inconsistency—that is, when different types of data (e.g. ultrasound video data and robotic control data) are transmitted at different rates—pose a unique challenge to telerobotic ultrasound systems and multimodal systems in general. While a delay of 250 ms is not perceivable in terms of isolated visual feedback, a delay of this magnitude is perceived when it represents a delay between commanding an action (such as movement of an ultrasound probe) and receiving visual feedback (such as the resulting ultrasound image).^{55,61}

Latency experienced during telerobotic ultrasound examinations is highly variable in published studies, primarily reflecting available bandwidth. Arbeille et al. found a 2 second latency between the instance that ultrasound probe manipulation commands were sent from the sonographer-site to when the resulting dynamic ultrasound images were received at the sonographer-site. In this study, telerobotic ultrasound examinations were performed at two medical centres 50–60 km away from the sonographer-site at a larger hospital in France, with an available bandwidth of 1 megabits/s (Mbps) and ultrasound video frame rate of 10 frames/s.⁶² In Sweden, Boman et al. found that broadband capacity of 20 Mbps (with less than 3% packet loss) was required to ensure transmission delay less than 200 ms. Latency was primarily attributable to transfer of videoconferencing data (150 ms) rather than data for controlling the robotic arm (30 ms).⁶³ In a more recent study, no latency was experienced by the sonographer when using a bandwidth of up to 100 Mbps between New York and Burlington, Massachusetts, and up to 50 Mbps between Munich and Boston.⁵⁶ The advent of 5G telecommunications technology in the future should significantly increase data transmission capacity and may resolve the issues of latency.

2.2.1.3 Pre-clinical telerobotic ultrasound systems

Much research in telerobotic ultrasound has focused on the development of ultrasound probe manipulators to allow sonographers to remotely perform the five basic movements of sliding, rocking, tilting, rotating, and compression as required for ultrasound scanning.⁶⁴ To

achieve at least some of these basic movements, predominant designs in the literature include spherical wrists and jointed arms, with DOFs ranging from three to seven. A summary of telerobotic ultrasound systems described in the literature is presented in Table 2.1.

One of the foremost groups contributing to the development of telerobotic ultrasound systems is the former Vision and Robotics Laboratory, now the PRISME Laboratory, at the University of Orleans in France, which developed a series of telerobotic ultrasound systems which are precursors of the now commercialized MELODY system (Société AdEchoTech, Naveil, France).^{51,65–68} In 1999, Gourdon et al. described a telerobotic ultrasound system named SYRTECH, a 3-DOF robot which contacted the patient's body through a ring-like frame. Using a joystick controller, sonographers could remotely control movements of an ultrasound probe.⁶⁵ Development was further advanced through support of the European Space Agency, and TERESA, OTELO, ESTELE (commercialized by Robosoft, Bidart, France), and PROSIT are telerobotic ultrasound systems emerging from this work, each based on a spherical wrist design.^{66–68}

More recently, the size of the probe manipulator was reduced by adding small internal motors to a commercial ultrasound probe.⁶⁹ The motorized probe allows sonographers to remotely tilt and rotate the probe, though other movements, including translation, must be made by an assistant at the patient-site based on guidance provided by the sonographer. This design does not include a frame which is held by the patient-site assistant; rather, the assistant directly holds the ultrasound probe.⁶⁹ A cohort study comparing motorized probes to a spherical wrist-like robotic arm found, based on anecdotal reports, that general practitioners who performed the examinations at the patient-site under the guidance of a sonographer felt that the motorized probe system was more ergonomic and easier to use.⁶⁹ However, the study did not directly compare the diagnostic performance of each method of scanning in a case-crossover design.

Recent efforts have increasingly explored the use of multipurpose robotic arms to hold an ultrasound probe, with most having a jointed arm design with six or seven DOFs. For example, Mathiassen et al. evaluated a 6-DOF collaborative, industrial robot (UR5, Universal Robots, Odense, Denmark) for telerobotic ultrasound. Requirements for force sensor control, haptic device control, and ultrasound image transfer were defined and achieved using the UR5-based

Table 2.1. Summary of pre-clinical telerobotic ultrasound systems

	First author(s)	Year	Institution of first author	Country of development	Name of system	Design	Target clinical applications
20	Pierrot et al. ⁷⁰	1999	LIRMM	France	Hippocrate	6-DOF jointed arm	Carotid and femoral arteries
	Gourdon et al. ⁶⁵	1999	ENSIB	France	SYRTECH	3-DOF modified wrist	General
	Salcudean et al. ⁷¹	2000	University of British Columbia	Canada	–	6-DOF parallelogram linkage	Carotid arteries
	Masuda et al. ⁷²	2001	Ehime University	Japan	–	6-DOF; four jointed legs on rails	Abdomen
	Mitsuishi et al. ⁷³ and Koizumi et al. ⁷⁴	2001-2009	University of Tokyo	Japan	–	7-DOF jointed arm	General, including shoulder
	Vilchis et al. ⁷⁵ and Banihachemi et al. ⁷⁶	2003, 2008	TIMC/IMAG Laboratory	France	TER	6-DOF wrist and platform on motor-driven cables	Abdominal and obstetric
	Vieyres et al. ⁶⁶	2003	University of Orleans	France	TERESA	4-DOF spherical wrist and platform	General
	Vieyres et al. ⁶⁷	2006	University of Orleans	France	OTELO	6-DOF wrist and platform	General
	Vilchis-Gonzalez et al. ⁷⁷	2007	Autonomous University of the State of Mexico	Mexico	TERMI	4-DOF rigid arm	Lower limb veins
	Solazzi et al. ⁷⁸	2007	Scuola Superiore Sant’Anna	Italy	EchoDev	5-DOF parallelogram with rotational joints	Peripheral arteries
	Janvier et al. ^{79,80}	2008-2014	University of Montreal	Canada	–	6-DOF jointed arm (commercialized F3 Articulated Robot, CRS Robotics)	Peripheral arteries
	Ito et al. ⁸¹	2010	Waseda University	Japan	FASTele	4-DOF “wearable” robot	FAST

Carbone et al. ⁸²	2010	University of Cassino	Italy	WTA-1R	6-DOF parallel mechanism	Carotid arteries
Nakadate et al. ⁸³	2010	Waseda University	Japan	WTA-2	3-DOF serial manipulator	Abdomen
Najafi et al. ⁸⁴	2011	University of Manitoba	Canada	—	4-DOF wrist	General
Masuda et al. ⁸⁵	2011	Tokyo University of Agriculture and Technology	Japan	—	6-DOF; three jointed legs	General
Nouaille et al. ⁶⁸	2012	University of Orleans	France	ESTELE	4-DOF serial spherical wrist and platform*	General
Nouaille et al. ⁶⁸	2012	University of Orleans	France	PROSIT	4-DOF wrist and platform	General
Sengupta et al. ⁵⁶	2014	Icahn School of Medicine at Mount Sinai	United States	—	7-DOF jointed arm† (based on the commercialized Cyton Gamma configuration servo-actuated robotic arm, Energid Technologies)	Echocardiography and carotid arteries
Monfaredi et al. ⁸⁶	2015	Children's National Medical Center	United States	—	6-DOF parallel mechanism	General
Seo et al. ^{87–89}	2015–2018	Korea Institute of Machinery and Materials	South Korea	—	6-DOF Stewart platform	General
Pahl and Supriyanto ⁹⁰	2015	Ilmenau University of Technology	Germany	—	5-DOF Cartesian coordinate robot	Cervix
Arbeille et al. ⁶⁹	2016	Unite Medecine Physiologie Spatiale	France	—	DOF not specified; ultrasound probe directly fitted with small internal motors to tilt and rotate the probe (“motorized probe”)	General

Mathiassen et al. ⁹¹	2016	King's College London	United Kingdom	—	6-DOF jointed arm (based on the commercialized UR5, Universal Robots collaborative robot)	General
Fang et al. ⁹²	2017	Johns Hopkins University	United States	—	6-DOF jointed arm (based on the commercialized UR5, Universal Robots collaborative robot)	General
Sharifi et al. ⁹³	2017	Shiraz University, University of Alberta, and Sharif University of Technology	Iran and Canada		Impedance-controlled teleoperation system using a 3-DOF robot (Phantom Premium 1.5A robot, Geomagic) and 2-DOF robot (Quanser) as the master and slave robots, respectively	Imaging of moving anatomic structures, such as the chest or heart
Arent et al. ⁹⁴ and Giuliani et al. ⁹⁵	2017-2020	Wroclaw University of Science and Technology	Poland	ReMeDi	Integrated robotic system comprised of a 7-DOF manipulator for performing ultrasound examinations, a 6-DOF manipulator for palpation, a mobile base, and integrated videoconferencing system	Echocardiography and abdominal
Lindenroth et al. ⁹⁶	2019	King's College London	United Kingdom	—	6-DOF soft robotics platform	Obstetric
Wang et al. ⁹⁷	2019	King's College London	United Kingdom	iFIND	7-DOF Cartesian configuration (v. 1) 5-DOF light-weight wrist unit, 2-DOF two-bar arm-based set of parallel link mechanisms with a 1-DOF rotational axis (v. 2) 17-DOF with two robotic arms	Obstetric and abdominal

Mathur et al. ⁹⁸	2019	University of Maryland	United States	–	holding and controlling two ultrasound probes (v. 3) 7-DOF jointed arm (based on a commercialized KUKA collaborative robot)	FAST
Victorova et al. ⁹⁹	2019	Hong Kong Polytechnic University	China	–	6-DOF jointed arm (based on the commercialized UR3, Universal Robots collaborative robot)	Scoliosis assessment
Huang et al. ¹⁰⁰	2019	Northwestern Polytechnical University	China	–	6-DOF jointed arm (based on a commercialized Epson C4, Seiko Epson robotic arm)	Multiple applications with 3D volume reconstruction
Abbasimoshaii et al. ¹⁰¹	2019	Tarbiat Modares University	Iran	–	Novel cabling mechanism; DOF not specified	Abdominal and pelvic
Sandoval et al. ¹⁰²	2020	University of Poitiers	France	–	7-DOF jointed arm (based on a commercialized Franka Emika collaborative robot)	General
Tsumura et al. ¹⁰³	2020	Waseda University	Japan	–	5-DOF; two linear stages and three-axis spring-based passive joints	Obstetric
Zhang et al. ¹⁰⁴	2020	Yunnan Open University	China	–	6-DOF jointed arm	Color Doppler; not otherwise specified
Geng et al. ¹⁰⁵	2020	Shanghai Jiao Tong University	China	–	6-DOF jointed arm (based on the commercialized UR5, Universal Robots collaborative robot)	General

* ESTELE was subsequently commercialized by Robosoft (Bidart, France) using the same name.

† Telerobotic ultrasound system developed by TeleHealthRobotics (Chicago, United States), though currently not commercially available.

DOF, degrees-of-freedom; FAST, focused assessment with sonography for trauma.

system, though no clinical assessment was performed.⁹¹ The UR5 robotic arm was also used by Fang et al. with the goal of creating an ergonomic co-robotic system to reduce the amount of force which sonographers must apply when scanning a patient.⁹² A group in the United States developed a telerobotic ultrasound system based on a lightweight, commercially available 7-DOF servo-actuated robotic arm (Cyton Gamma configuration, Energid Technologies, Cambridge, Massachusetts) attached to a customized holder for a standard linear ultrasound probe. Movement of the ultrasound probe was remotely controlled using a computer mouse. A videoconferencing system included three cameras at the patient-site. Feasibility studies were conducted on a two-vessel, vascular access simulation phantom.⁵⁶

The Remote Medical Diagnostician (ReMeDi) project sought to develop an integrated robotic system enabling physicians to remotely perform assessments, including patient interviews, physical examinations (including observation, auscultation, and palpation), and ultrasound examinations. The system is comprised of a 7-DOF manipulator for performing ultrasound examinations, a 6-DOF manipulator for palpation, a mobile base allowing the robot to position beside a patient and move between patients, and an integrated videoconferencing system.⁹⁴ Among 12 physicians who assessed the feasibility of the ReMeDi system for abdominal and obstetrical ultrasound examinations, all agreed the system has potential to be introduced into clinical practice. Limitations including synchronizing the orientation of ultrasound probes at the patient-site and sonographer-site, the loud noise of the robotic arm, and intermittent rapid and unpredictable movements of the robotic arm were identified and subsequently addressed in a second prototype.^{95,106}

2.2.1.4 Commercial telerobotic ultrasound systems

Research and development in the PRISME Laboratory in France led to the commercialization of ESTELE, manufactured by Robosoft (Bidart, France), and subsequently MELODY, manufactured by Société AdEchoTech (Naveil, France).⁵¹ The MELODY system is a 3-DOF probe manipulator which, similar to its predecessors, allows the ultrasound probe to contact the patient's body through a ring-like frame which is supported by a floor-mounted stand (Figure 2.4). In contrast to other systems which used a computer mouse and graphical user interface to control the movements of the manipulator, the MELODY system uses a mock ultrasound probe with sensors to dynamically assess the position of the mock probe and

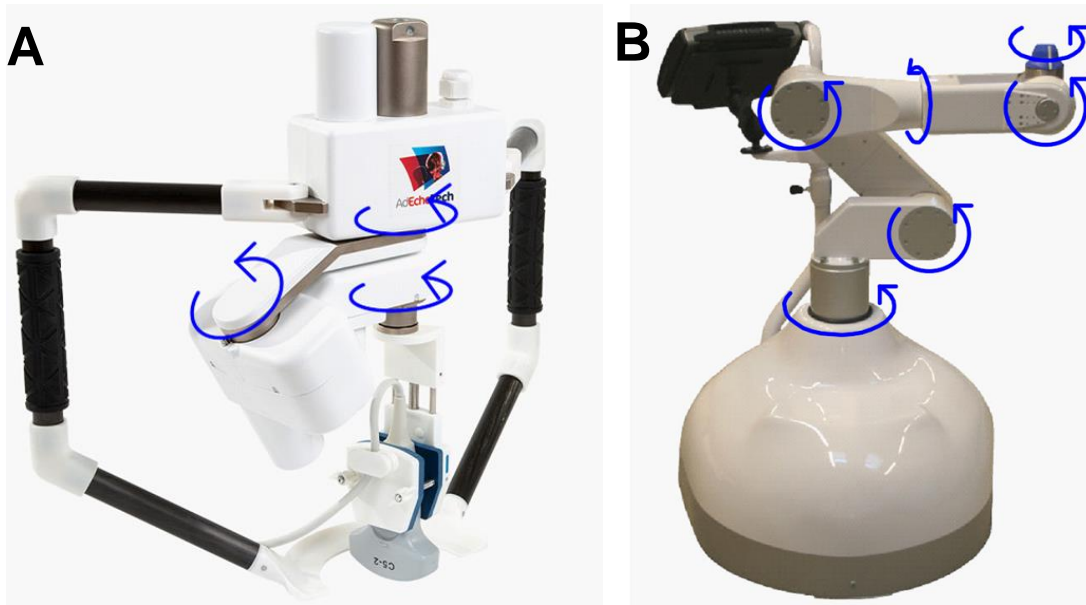


Figure 2.4. Two robotic arm designs for telerobotic ultrasound. (a) Robotic arm of the MELODY patient system (AdEchoTech, Naveil, France), based on a spherical wrist design with 3-DOF (blue curved arrows), with demonstrated applications for abdominal and obstetrical ultrasound. (b) Robotic arm of Medirob Tele (Medirob AB, Skellefteå, Sweden), a 6-DOF serial robot with demonstrated applications for echocardiography. Images courtesy of Société AdEchoTech and Medirob AB, respectively; used with permission.

subsequently replicate movements at the patient-site. Movements of the scanning ultrasound probe, including rocking, tilting, and rotating, are remotely controlled by manipulating a mock probe at the sonographer-site, though an assistant at the patient-site controls sliding and compression of the ultrasound probe on the patient's body as instructed by the sonographer.^{5,51,54,55} Submission of Section 510(k) premarket notification of intent to market the device was acknowledged by the United States Food and Drug Administration in June 2017, clearing the device for commercial distribution with clinical indications including abdominal, pelvic, urologic, fetal, pediatric, small parts, and peripheral vascular imaging.⁵² A medical device licence for MELODY was granted by Health Canada in June 2018.¹⁰⁷

As the robotic manipulator holds an ultrasound probe, the telerobotic system can potentially be used with any ultrasound system. Adams et al. described the MELODY system integrated with the SonixTablet ultrasound system (BK Ultrasound, Richmond, Canada). All images from the ultrasound unit located at the patient site were also displayed on a monitor at the

sonographer site. Settings from the ultrasound unit could be controlled remotely by the sonographer using a touchscreen computer. A videoconferencing system (TE30 All-in-One, HD Videoconferencing Endpoint, Huawei Technologies, Shenzhen, China) between the patient and expert sites allowed the patient, sonographer, and patient-site assistant to communicate with each other.^{5,54}

A telerobotic ultrasound system specifically for echocardiography, Medirob Tele, was developed by Medirob AB (Skellefteå, Sweden).^{53,63} The system consists of a 6-DOF serial robot. In contrast to the MELODY system which is controlled by a mock probe, Medirob Tele is controlled by a 3D mouse.¹⁰⁸ While it is recommended that an assistant be in the room of the patient during examinations, an assistant is not responsible for controlling pressure or gross placement of the robotic arm on the patient's body.⁵³ A sensor measures the pressure applied on the patient's body and displays the value on the sonographer's monitor.⁶³ Similar to the MELODY system, the robot can be used with any ultrasound unit; however, full remote control of all ultrasound settings is currently only available with ultrasound units from specific vendors.⁵³ While initially developed to perform long distance imaging in geographic areas in which a sonographer is not available, the Medirob system has also been marketed to reduce musculoskeletal injuries among sonographers.¹⁰⁸

Most recently, Sensing Future (Coimbra, Portugal), in collaboration with the University of Coimbra, Luz Saúde, and the Instituto Pedro Nunes, adapted a 6-DOF serial robot with haptic feedback to perform abdominal ultrasound examinations as part of the Robot Sensing for Tele-Ecography (ROSE) project. The robot is controlled by manipulating a desktop haptic device which is a miniature version of the 6-DOF robotic arm.¹⁰⁹

2.2.1.5 Real-time remotely mentored ultrasound

Portable, low-cost ultrasound units are rapidly becoming commercially available, including solutions with functionality to allow clinicians to remotely view ultrasound images generated in real-time.¹¹⁰ While these systems do not allow remote users to control movements of the ultrasound probe or control ultrasound settings, they facilitate real-time remotely mentored ultrasound to consult with colleagues during scanning.¹¹¹ They may also be used in combination with previously discussed probe manipulators as part of a telerobotic ultrasound system.

Philips (Amsterdam, Netherlands) partnered with Innovative Imaging Technologies (Montreal, Canada) to integrate Reacts, a secure, collaborative platform with interactive tools for

remote virtual guidance, supervision and training, with its portable ultrasound probe product, Lumify.^{110,112} Reacts allows users to collaborate with a colleague through a “tele-ultrasound call” with sharing of ultrasound video and video and audio from a tablet computer.¹¹⁰ A similar product, Butterfly iQ (Butterfly Network, Guilford, Connecticut)—a portable ultrasound probe—allows users to transfer images to and communicate with colleagues via text messaging in real time.¹¹³ Software which prompts users to adjust ultrasound probe positioning to optimize image quality has recently been launched for echocardiography¹¹⁴ and lung imaging¹¹⁵ (the latter available for educational use only) as another potential aid for those with less experience with ultrasound scanning.

There is limited evidence regarding the impact of a “remote virtual mentor” on diagnostic accuracy.¹¹⁶ As ultrasound imaging is a dynamic modality which requires users to actively identify pathology throughout scanning rather than simply document minimum required images, it is anticipated that users must have strong baseline ultrasound skills to effectively use a remote virtual mentor for completion of an entire diagnostic examination if the remote virtual mentor is not able to directly control the ultrasound probe. For certain examinations, however, remote guidance without telerobotic technology may be preferable. Arbeille et al. found that remote guidance using an ultrasound system in which experts could remotely control ultrasound settings while a general practitioner performed the examination was preferable to using a robotic arm or motorized probes for interrogation of superficial vessels.⁶⁹ Examination type and skills of the assistant or clinician at the patient-site will be key considerations in determining an optimal solution for remote ultrasound. Further, distinction must be made between point-of-care ultrasound performed by non-imaging clinicians, and diagnostic ultrasound supervised by radiologists, obstetricians, or cardiologists.^{43,117} Point-of-care ultrasound refers to focused sonographic assessments intended to clarify specific findings, often in an acute or emergent setting, by non-imaging clinicians providing care. Consultative diagnostic ultrasound refers to ultrasound examinations supervised by consultant imaging specialists following a consultation request usually from a non-imaging physician. These examinations follow a systematic approach with specific requirements for image archiving, documentation of findings, and communication to referring clinicians.⁴³ Real-time mentored teleultrasound may help facilitate the type of focused assessments typical of point-of-care ultrasound, though it remains unclear what role it

may have in facilitating remote diagnostic ultrasound if the remote virtual mentor is not able to remotely control the ultrasound probe directly.

2.2.2 Clinical applications

Many studies describing telerobotic ultrasound systems at early stages of technological development have presented limited assessments, demonstrating the utility of the system in imaging a phantom model or performing an ultrasound examination on one or a few patients with no robust clinical measures.^{84,85} More recently, as telerobotic ultrasound systems have evolved, clinical studies have assessed the feasibility and diagnostic accuracy of telerobotic ultrasound for abdominal,^{5,97,118–121} obstetrical,^{54,122} echocardiography,^{118,123} and trauma imaging.⁷⁶ These studies have primarily employed a case-crossover design with conventional ultrasound as the reference standard (Table 2.2). Telerobotic ultrasound systems have also been used to assess the thyroid, leg veins, carotid arteries, and musculoskeletal structures;^{62,124} however, these studies are case series with no comparison to a reference standard for assessment of diagnostic accuracy.

2.2.2.1 Abdominal imaging

Published clinical studies assessing telerobotic ultrasound systems for abdominal ultrasound have been conducted in Canada and France. Studies in France have focused on evaluation of precursors of the MELODY system,^{118–121} while a study was conducted in Canada investigating feasibility and clinical performance of the currently commercialized MELODY system.⁵ A study evaluating an early-stage telerobotic ultrasound system with limited clinical assessment was also conducted in the United Kingdom.⁹⁷

Arbeille et al. assessed an early version of a telerobotic ultrasound system for abdominal and pelvic imaging in 20 patients in a case-crossover study.¹¹⁸ To simulate remote scanning, patients and the remote sonographer were located in different rooms of the same hospital. Longitudinal and transverse images of the liver (right lobe), gallbladder, portal vein, aorta, pancreas, kidneys, bladder, prostate/uterus and ovaries were successfully acquired in all 20 cases. Satisfactory images of the spleen could not be acquired in four of the 20 cases (20%). Results for visualization of important anatomy such as the common bile duct and left lobe of the liver were not reported, and the ability for telerobotic ultrasound to identify pathology was not assessed.¹¹⁸

In a subsequent study, Courreges et al. compared telerobotic ultrasound and conventional ultrasound for abdominal assessments. Of 32 telerobotic examinations, the liver was adequately

Table 2.2. Summary of published clinical trials of telerobotic ultrasound

Reference	Year of publication	Country of first author	Type of examinations	Study Design	Number of patients enrolled	Primary and secondary outcomes
Arbeille et al. ¹¹⁸ ; preliminary results in Vieyres et al. ⁶⁶	2003	France	Abdominal, pelvic, cardiac	Case-crossover	20	Liver (right lobe), gallbladder, portal vein, aorta, pancreas, kidneys, bladder, prostate/uterus and ovaries were visualized telerobotically in 20 of 20 cases (100%). (Visualization of the common bile duct and left lobe of the liver was not reported.) Cardiac four-chamber view and long-axis views of the spleen were not obtained in 2 of 20 (10%) and 4 of 20 (20%) of telerobotic cases, respectively.
Arbeille et al. ¹²⁵	2004	France	Variable	Case-crossover	105	Complete investigation (visualization) of organs requested for each clinical case was obtained in 80 of 105 telerobotic examinations (76%) compared to 91 of 105 conventional examinations (87%). Duration of telerobotic examinations was 45% higher for telerobotic examinations (16 ± 10 min) than conventional examinations (11 ± 4 minutes).
Courreges et al. ¹¹⁹	2005	France and Spain	Abdominal	Case-crossover	52 (includes 20 patients also reported in Arbeille et al. ¹¹⁸ and Vieyres et al. ⁶⁶)	Of 32 telerobotic examinations, the liver was adequately visualized in 91% of cases; kidneys, spleen and gallbladder in 85% of cases, and pancreas in 64% of cases. 38 of 57 lesions (66%) detected using conventional ultrasound were also identified using telerobotic ultrasound. Of the patients who presented with symptoms, telerobotic examinations enabled a diagnosis in 10 of 12 cases (83%). Results of the 20 patients included in Arbeille et al. ¹¹⁸ and Vieyres et al. ⁶⁶ are as above.
Arbeille et al. ¹²² ; also presented in an abridged form in Arbeille et al. ¹²⁶	2005	France	Obstetric	Case-crossover	29	Fetal presentation, placenta location and echogenicity, and amniotic fluid volume were concordant between all telerobotic and conventional examinations. Telerobotic and conventional measurements of biometric parameters were within $\pm 5\%$ in all cases, though in two cases femur length could not be measured within the maximum 5 minute time constraint. Results regarding visualization of additional fetal anatomic structures were not presented. Telerobotic examinations were 29% longer than conventional examinations (mean 18 minutes vs. 14 minutes for telerobotic

						and conventional examinations, respectively).
Martinelli et al. ¹²⁰ ; also reported in an abridged form in Banihachemi et al. ⁷⁶	2007	France	Abdominal aorta and common iliac arteries only	Case-crossover	58	<p>54 of 58 examinations were successfully completed (4 examinations experienced technical failures). 8 of 8 abdominal aortic aneurysms (100%) detected using conventional ultrasound were also detected using telerobotic ultrasound.</p> <p>Interobserver correlation coefficient for measurement of abdominal aortic diameter was 0.982.</p> <p>Kappa-value of concordance in evaluating atheromatosis using conventional vs. telerobotic ultrasound was 0.84 ± 0.11.</p> <p>Median duration \pm SD of telerobotic examinations was 17 ± 8 minutes compared to 12 ± 7 minutes for conventional examinations ($p < 0.001$ based on t-test).</p> <p>Global quality evaluation scores were 75.6 ± 15 for telerobotic examinations compared to 87 ± 12.5 for conventional examinations.</p>
Arbeille et al. ¹²¹ ; also presented in an abridged form in Arbeille et al. ¹²⁶	2007	France	Abdominal	Case-crossover	87	<p>At least one organ could not be adequately assessed in 11 of 87 telerobotic examinations (13%).</p> <p>26 of the 35 lesions (74%) detected with conventional ultrasound were also detected with telerobotic ultrasound.</p> <p>Telerobotic examinations were 43% longer than conventional examinations (16 ± 10 minutes compared to 11 ± 4 minutes).</p>
Banihachemi et al. ⁷⁶	2008	France	FAST	Case-crossover	11	<p>Telerobotic examinations were successfully performed in 10 of 11 patients (90%). No visceral trauma was detected using telerobotic ultrasound nor conventional ultrasound in any cases.</p> <p>Telerobotic examinations were 189% longer than conventional examinations (26 minutes compared to 9 minutes).</p> <p>Transfer to another hospital for a radiologist-performed examination was avoided for 10 of 11 patients (90%).</p> <p>Results for assessment of the abdominal aorta are described in further detail in Martinelli et al.¹²⁰</p>
Arbeille et al. ¹²³	2014	France	Cardiac	Case-crossover	41	<p>61 of 71 valve leaks or aortic stenoses (86%) identified using conventional ultrasound were also detected using telerobotic ultrasound. No false positives were identified.</p> <p>Left ventricular ejection fraction, aortic flow and right</p>

						ventricular ejection fraction were measured in 95%, 93% and 100% of cases, respectively, using telerobotic ultrasound. No statistically significant difference was identified in the majority of measurements assessed using conventional vs. telerobotic ultrasound; however, differences in measurements of left ventricle diastolic volume and aortic blood flow velocity were statistically significant.
Boman et al. ¹²⁷	2014	Sweden and United States	Cardiac	Randomized controlled trial	38	Total process time for cardiology consultation (time from initial examination by a general practitioner until completion of the specialist consultation) decreased from a median of 114 days in the standard of care arm to 26.5 days in the arm with telerobotic ultrasound and teleconsultation ($p < 0.001$).
Georgescu et al. ¹²⁴	2016	France	Abdomen, pelvis, lower limb veins, supraaortic vessels, thyroid, small parts, obstetric	Case series	300	Telerobotic ultrasound could not be achieved in 10 of 300 cases (3%). Average duration of telerobotic examinations was 24 ± 5 minutes.
Arbeille et al. ⁶²	2016	France	Abdomen, pelvis, carotid arteries, lower limb veins, thyroid, MSK, obstetric	Case series	100	97 of 100 (97%) of telerobotic examinations were of sufficient quality for diagnosis. Average duration of telerobotic examinations was 17 ± 4 minutes.
Arbeille et al. ⁶⁹	2016	France	Abdomen, pelvis, carotid arteries, thyroid, MSK, obstetric	Cohort study	340	Examinations were performed using a robotic arm ($n = 47$), motorized probes ($n = 92$), and non-telerobotic remote guidance ($n = 201$). Telerobotic examinations provided sufficient information for a safe diagnosis in 329 of 340 examinations (97%). Results were not stratified by method of scanning. Examinations with motorized probes were significantly shorter than with the robotic arm ($p = 0.012$). Remote guidance examinations in which the expert could modify ultrasound settings were significantly shorter than remote guidance examinations in which the non-expert adjusted settings ($p = 0.017$).

Adams et al. ⁵	2017	Canada	Abdominal	Case-crossover		Of organs visualized sufficiently on conventional exams, 92% were also sufficiently visualized on telerobotic examinations. No statistically significant differences between telerobotic and conventional measurements of the liver, spleen, and proximal aorta were observed; however, telerobotic assessments overestimated or underestimated distal aorta, common bile duct, and kidney measurements. Three imaging findings were detected by conventional scanning only, two imaging findings were detected by telerobotic scanning only, and five imaging findings were detected by both telerobotic and conventional scanning. All patients surveyed would be willing to have a telerobotic examination in the future.
Adams et al. ⁵⁴	2018	Canada	Obstetric	Case-crossover	30 (limited examination: n = 20; detailed examination: n = 10)	Excellent agreement between telerobotic and conventional measurements of all four biometric parameters was observed (intraclass correlations >0.90). An average of 80% of the 21 fetal structures attempted in the study protocol were sufficiently visualized using the telerobotic system, with visualization ranging from 57%–100% per patient. 97% of patients surveyed would be willing to have a telerobotic examination in the future.
Wang et al. ⁹⁷	2019	United Kingdom	Abdominal	Case-crossover	20 (18 included in analysis)	“Good” or “acceptable” quality images of the liver, pancreas, and abdominal aorta in 96.6% of images obtained conventionally vs. 90.8% of images obtained telerobotically. Images of the gallbladder, spleen, kidneys, and bladder were not reliably obtained using the telerobotic ultrasound system and were not included in the analysis.

FAST, focused assessment with sonography for trauma; MSK, musculoskeletal; SD, standard deviation.

visualized in 91% of cases; kidneys, spleen and gallbladder in 85% of cases, and pancreas in 64% of cases. Further, the study assessed the clinical utility of telerobotic ultrasound for diagnosis: 38 of 57 lesions (66%) detected using conventional ultrasound were also identified using telerobotic ultrasound, and of the patients who presented with symptomatic pathology, telerobotic examinations enabled a diagnosis in 10 of 12 cases (83%).¹¹⁹

Another study, also from France, investigated telerobotic ultrasound specifically for assessment of the abdominal aorta and common iliac arteries.¹²⁰ All eight abdominal aortic aneurysms (100%) detected using conventional ultrasound were also detected using telerobotic ultrasound. Interobserver correlation coefficient for measurement of aortic diameter was 0.982, and the kappa-value \pm standard deviation of concordance in evaluating atheromatosis using conventional vs. telerobotic ultrasound was 0.84 ± 0.11 .

As a follow-up to their 2003 study, Arbeille et al. assessed a precursor of the MELODY system for abdominal ultrasound, with an additional focus on assessment of pathology using the telerobotic ultrasound system. Twenty-six of 35 lesions (74%) identified by conventional scanning were also identified with telerobotic ultrasound, and at least one organ could not be adequately assessed in 11 of 87 telerobotic examinations (13%).¹²¹

As telerobotic ultrasound systems have advanced to commercialization, Adams et al. evaluated the currently commercialized MELODY system (Société AdEchoTech, Naveil, France) for abdominal ultrasound.⁵ As an advancement over previously assessed systems, the MELODY system allowed sonographers or radiologists to control image settings and manipulate the mock probe as if they were controlling a real ultrasound probe. A patient-site assistant with no prior experience using ultrasound controlled gross movements of the robotic frame on the patient's abdomen as instructed by the sonographer. Conventional abdominal ultrasound examinations were prospectively performed on 18 patients, followed by a telerobotic ultrasound examination using the MELODY system with a standard ultrasound unit (SonixTablet, BK Ultrasound, Richmond, Canada). Ninety-two percent of all organs included in a standard abdominal ultrasound protocol were visualized by telerobotic ultrasound, provided they were also visualized by conventional scanning. Three imaging findings were detected by conventional scanning only, two imaging findings were detected by telerobotic scanning only, and five imaging findings were detected by both telerobotic and conventional scanning. The fact that lesions not identified through conventional scanning were detected using telerobotic scanning

(and did in fact represent true lesions rather than false positives) highlights the operator-dependent nature of ultrasound imaging and the imperfect nature of using conventional ultrasound as a reference standard in studies assessing telerobotic ultrasound. Telerobotic scans took longer than conventional scans (mean duration of 39.9 minutes vs. 15.7 minutes), though telerobotic ultrasound was well-received by patients: each patient surveyed indicated their willingness to have a telerobotic examination in the future.⁵

2.2.2.2 Obstetrical imaging

Similar to abdominal ultrasound, case-crossover studies assessing telerobotic ultrasound systems for obstetrical ultrasound have been conducted in Canada and France. A study in France evaluated a precursor of the MELODY system,¹²² while a study in Canada (as will be presented in Chapter 6 of this thesis) investigated the feasibility and clinical performance of the currently commercialized MELODY system for obstetrical ultrasound.⁵⁴

In a study assessing a precursor of the MELODY system, Arbeille et al. found that fetal presentation, placenta location and echogenicity, and amniotic fluid volume were concordant between all telerobotic and conventional examinations. Biometric parameters measured telerobotically and conventionally were within $\pm 5\%$ in all cases except two cases in which femur length was not measured within the maximum 5 minute time constraint. Scanning of additional anatomic structures was attempted; however, results regarding the ability of the telerobotic ultrasound system to acquire all required images for a complete second trimester ultrasound examination were not presented.¹²²

As telerobotic ultrasound systems have evolved since studies assessed early prototypes and as telerobotic ultrasound systems are now commercially available, it is critical to assess this technology and determine its diagnostic capability and acceptability for clinical use. As presented in Chapter 6, Adams et al. evaluated the MELODY system for both limited and complete obstetrical examinations.⁵⁴ In a case-crossover study design, limited ultrasound examinations assessing biometry, placenta location, and amniotic fluid were performed on 20 participants conventionally and telerobotically. Detailed ultrasound examinations, assessing biometry, placenta location, amniotic fluid, and fetal anatomy, were performed on 10 participants conventionally and telerobotically. For all four biometric parameters, intraclass correlations between measurements obtained telerobotically and conventionally were >0.90 , indicating excellent agreement. An average of 80% of the 21 anatomical structures attempted in the study

protocol were visualized sufficiently by telerobotic scanning, with visualization ranging from 57%–100% per patient.⁵⁴

2.2.2.3 Echocardiography

In a 2003 study, Arbeille et al. found that a four-chamber view of the heart was generated in 18 of 20 cases (90%) using an early telerobotic ultrasound system; however, a full echocardiographic assessment was not undertaken.¹¹⁸ In a subsequent study in 2014 prospectively enrolling 41 patients, Arbeille et al. found 61 of 71 aortic stenoses or valve leaks (86%) identified using conventional ultrasound were also detected using telerobotic ultrasound. Left ventricular ejection fraction, aortic flow and right ventricular ejection fraction was measured in 95%, 93% and 100% of cases, respectively, using telerobotic ultrasound. No statistically significant difference was identified in most measurements acquired through conventional and telerobotic scanning; however, statistically significant differences in measurements of aortic blood flow velocity and left ventricular diastolic volume were identified.¹²³

2.2.2.4 Trauma imaging

In a study assessing a telerobotic ultrasound system for focused assessment with sonography for trauma (FAST), scans were successfully completed using a telerobotic ultrasound system in 10 of 11 patients (90%), eliminating the need for transfer to a different hospital for these 10 patients.⁷⁶ However, no findings were detected using telerobotic ultrasound nor conventional ultrasound in all cases, limiting the ability to draw conclusions regarding the diagnostic accuracy of telerobotic ultrasound for FAST scans.

2.2.3 Telerobotic ultrasound clinics

2.2.3.1 Feasibility

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

Arbeille et al. performed 100 telerobotic ultrasound examinations using motorized probes in four medical centres 50 km, 60 km, 1800 km, and 7000 km from a hospital in France at which a radiologist was based. These included examinations of the abdomen and pelvis (n=36), vascular structures (n=42), small parts (n=22), as well as prenatal examinations (n=15). They

found that 97% of examinations were of sufficient quality for diagnosis, though no comparison to a reference standard was conducted.⁶² A French group also evaluated the use of telerobotic ultrasound at a remote medical centre and a seniors' home, each 50 km away from the sonographer-site at the hospital. Over a one year period, 300 telerobotic examinations were performed, including 68 (23%) abdominal, 20 (7%) pelvic, 138 (46%) carotid arteries, 33 (11%) thyroid, 30 (10%) leg veins, and 11 (3.7%) kidney and urinary tract. Telerobotic ultrasound examinations were not successful in 10 of the 300 cases.¹²⁴

Boman et al. assessed the feasibility and clinical value of robot-assisted remote echocardiography and teleconsultation for heart failure patients in a region in northern Sweden.¹²⁷ Thirty-eight patients were randomized to either remote consultation and telerobotic ultrasound (echocardiography), or the standard of care which involved patients travelling to the nearest specialist hospital which was 65 miles away. They found that total process time for cardiology consultation (the time from initial examination by a general practitioner until completion of the specialist consultation) decreased from a median of 114 days in the standard of care arm to 26.5 days in the arm with telerobotic ultrasound ($p < 0.001$).¹²⁷ However, the sustainability of decreased time to diagnosis in the remote consultation arm over time and with a greater number of patients is unknown.

As demonstrated in clinical studies in France and Sweden, the development of telerobotic ultrasound clinics in northern and remote communities may enable patients to access ultrasound imaging in their home community. However, this model has yet to be developed in North America or, more specifically, in northern Saskatchewan, with its unique geography, culture, and healthcare practices. Determining the feasibility of using telerobotic ultrasound to establish a service delivery model to remotely provide ultrasound access to patients in rural and remote communities distributed over a large geographic region—and identifying potential operational challenges and solutions when deploying this model—are key knowledge gaps addressed in Chapters 7 and 8.

2.2.3.2 Cost analysis

Little evidence currently exists regarding cost analysis of telerobotic ultrasound. A group in northern Sweden assessed costs associated with traditional hospital diagnosis and distance diagnosis (utilizing telerobotic ultrasound for echocardiography) among patients with heart failure. Costs of the two approaches were similar based on the health authority's perspective,

though a distance diagnosis approach resulted in reduced costs based on a societal perspective, primarily due to reduction in travel for patients and patient-related expenses.¹²⁸ A cost analysis of a telerobotic ultrasound clinic to perform general diagnostic ultrasound exams, and a cost analysis of telerobotic ultrasound in a North American context, has yet to be undertaken. These key knowledge gaps, which are critical to informing decisions regarding implementation of this technology in health systems, are addressed in Chapter 9 of this thesis.

CHAPTER 3

ACCESS TO ULTRASOUND IMAGING: A QUALITATIVE STUDY IN TWO NORTHERN, REMOTE, INDIGENOUS COMMUNITIES IN CANADA*

As described in Chapter 2, substantial health inequities exist between northern and non-northern people and Indigenous and non-Indigenous people.^{6,7} While the origins of health inequities are multifactorial, access to healthcare services is an important determinant of health and a focus on access to healthcare services is an important aspect in ensuring health equity.⁴ A substantial body of literature has described access to healthcare services in general;^{45–48,129–132} however, there are gaps in the diagnostic radiology literature regarding access to medical imaging in underserved communities, including access to ultrasound imaging in northern, remote communities. To address these gaps, this chapter provides insights into northern, remote community members' perceptions of access to ultrasound imaging and factors which shape access to ultrasound imaging. These insights are valuable to inform efforts to improve access to ultrasound imaging in northern, remote communities. This chapter serves as an example of how a qualitative methodology, a methodology rarely used in the diagnostic radiology literature, can be used to explore disparities in medical imaging and inform the development of solutions which help improve equity in medical imaging.

* This chapter is based on:

Adams SJ, Babyn P, Burbridge B, Tang R, Mendez I. Access to ultrasound imaging: a qualitative study in two northern, remote, Indigenous communities in Canada. *Int J Circumpolar Health*. 2021;80(1):1961392. doi: 10.1080/22423982.2021.1961392.

3.1 Abstract

Objective: Ultrasound imaging is an essential component of healthcare services. This study sought to explore perceptions of access, and factors which shape access, to ultrasound imaging in two northern, remote, Indigenous communities in Canada.

Methods: Using interpretive description as a methodological approach and a multi-dimensional conceptualization of access to care as a theoretical framework, 15 semi-structured interviews were conducted in the northern Canadian communities of Stony Rapids and Black Lake, Saskatchewan. All participants had an obstetrical (n = 6) or non-obstetrical ultrasound exam (n = 10) performed in the past 10 years, including one participant who had both an obstetrical and general diagnostic ultrasound exam. Interviews were audio recorded and interview transcripts were analysed using constant comparative analysis.

Results: Geographic isolation from imaging facilities was a central barrier to participants accessing ultrasound imaging. Other barriers became apparent when participants had to travel for ultrasound, including fear of air travel, isolation from family, financial means, and unfamiliarity with larger cities. Barriers such as family and work responsibilities were exacerbated by the barrier of geography. Participants overcame these barriers as they appreciated diagnostic benefits of ultrasound imaging, and the ultrasound exam brought personal satisfaction in better understanding one's health and reassurance about the health of their baby.

Conclusion: This study highlights disparities in access to ultrasound imaging—a core imaging modality—for northern, remote, Indigenous populations. Future efforts to improve access to imaging should consider barriers of distance to imaging facilities and strategies to bridge these barriers.

3.2 Introduction

Medical imaging is an essential component of healthcare services. Together with radiography, ultrasound imaging is considered a basic imaging modality, and approximately 75-80% of imaging needs in developed countries are met with radiography and ultrasound imaging alone.^{133,134} Ultrasound offers several benefits for patient assessment as it is non-invasive and not associated with ionizing radiation. Ultrasound imaging is commonly used to assist in the

diagnosis of a wide variety of diseases and is also an established part of routine prenatal care.^{135,136}

However, access to ultrasound imaging remains limited for many people across the world. *Access* has been defined as “the opportunity to reach and obtain appropriate health care services in situations of perceived need for care”⁴⁸ or “the degree of ‘fit’ between the clients and the system”.⁴⁵ *Accessibility* is viewed as “the nature of the services that provide this opportunity [to access care]”⁴⁸ or the “degree of adjustment between the characteristics of health resources and the corresponding characteristics of the population in the process of seeking and obtaining services”.¹³⁷ Significant in each of these definitions is the dynamic interrelationship between health system characteristics and patient factors, which together determine access to care. Access to care is not simply dependent on the existence of healthcare services to meet health needs from a biomedical perspective; it also considers the degree to which care is available at facilities which individuals can reach and compatible with personal and cultural values. This interrelationship between individuals and the health system is also reflected in Levesque et al.’s framework of access to care.⁴⁸ In this framework, five dimensions of accessibility are conceptualized as *approachability*, *acceptability*, *availability* and *accommodation*, *affordability*, and *appropriateness*. Five corresponding abilities of individuals and populations interact with the dimensions of accessibility to generate access, namely the *ability to perceive*, *ability to seek*, *ability to reach*, *ability to pay*, and *ability to engage*.⁴⁸ This framework may have important implications when exploring access to imaging.

Access to healthcare is recognized as an important determinant of health.⁴ Suboptimal access to healthcare can result in delays in diagnosis and treatment, development of more advanced disease, and increased rates of complications.¹³² In northern Canada, the large geographic dispersion of communities result in ultrasound services being not locally available, and patients in many northern, remote communities must travel long distances to the closest ultrasound facility.¹³⁸ A large proportion of the population in northern Canada is Indigenous; in the Canadian province of Saskatchewan, over 85% of northern residents identify as Indigenous, and this proportion is as high as 96% in the northernmost part of Saskatchewan based on health authority boundaries.¹³⁹ Significant disparities in health status exist between Indigenous and non-Indigenous peoples in Canada.^{4,140} This may be due to a multitude of interrelated factors related

to colonial legacies, income, employment, housing, and education, as well as access to healthcare services.^{8,15}

There is a paucity of data regarding access to medical imaging and limited understanding of how access to imaging is conceptualized, particularly in northern, remote, Indigenous communities in Canada. Thus, we sought to answer the question: what are the perceptions of access, and factors which shape access, to ultrasound imaging among northern, remote, Indigenous community members in Saskatchewan, Canada? We specifically focused on ultrasound imaging due to the foundational importance of this imaging modality and the operator-dependent nature of this imaging modality resulting in it not being locally available in many northern, remote communities.¹⁴¹ We employed a qualitative research methodology to obtain a greater richness and depth of understanding surrounding access to imaging as shared through the narratives of interview participants. Improved understanding of the barriers which patients face by hearing directly from patients is critical to reduce health disparities; support culturally safe, patient- and family-centred care; and inform the development of solutions to better meet the imaging needs of populations.

3.3 Methods

3.3.1 Methodological approach and theoretical framework

Interpretive description, a qualitative research methodology which focuses on developing new understanding to inform clinical practice, was chosen as the methodological approach for this study due to its grounding in the health professions and its potential to generate evidence-based knowledge which is relevant to radiology practices and health systems.^{142–145} This methodology aims to capture the perceptions and experiences of groups of interest using a transparent research process,¹⁴⁴ which is ideally suited to addressing the research question posed. In this study, we drew upon rich narratives of individuals' experiences accessing ultrasound imaging as shared in semi-structured interviews. Similar to other qualitative research methodologies, interpretive description privileges depth of understanding and actionable improvements over broad generalizability. This methodological approach also values participant voices, an important feature of Indigenous methodologies.^{146,147}

Within this methodological approach, Levesque et al.'s conceptualization of access to care⁴⁸ was used as a theoretical framework for this study. This framework, along with clinical

expertise brought by the researchers and lived experience by community partners, informed development of the study design and interview guide and provided a lens through which to interpret findings. While this theoretical framework was used to help interpret findings, an inductive approach was employed in analysis of participants' narratives, allowing ideas which did not fit within the established framework to be incorporated into the analysis.^{142,144}

Postcolonial, decolonizing, and Indigenous perspectives were also applied to provide additional context regarding perceptions of access, and factors which shape access, to ultrasound imaging among northern, remote, Indigenous community members.^{19,148–151}

3.3.2 Setting

Black Lake and Stony Rapids—two northern Indigenous communities in the province of Saskatchewan, Canada—were chosen as the setting for this study (Figure 3.1). These two communities share characteristics of having a high proportion of people of Indigenous ancestry.



Figure 3.1. Black Lake and Stony Rapids, two northern, remote, Indigenous communities in the province of Saskatchewan. The closest cities with regularly available ultrasound imaging are Prince Albert and Saskatoon, approximately 903 km and 1,040 km (driving distance), respectively, from Stony Rapids.

In winter a seasonal road (ice road) connects the communities to the Saskatchewan rural road system; however, during the remainder of the year the communities are only accessible via air transportation.¹⁷

The community of Black Lake is part of the Black Lake Denesuline First Nation. Based on 2016 Census data, the population of Black Lake (Chicken 224 Indian Reserve) is 1,379. The average age of the population is 26.8 years and 96% of the population is younger than 65 years. Dene is the mother tongue of 93% of the population, and 98% of community members report English as their first official language spoken. Approximately 98% of community members are Registered or Treaty Indians (persons registered under the *Indian Act* of Canada or persons who are members of a First Nation or Indian band that signed a treaty with the Crown).¹⁵²

Stony Rapids is a northern hamlet 20 km away from Black Lake with a population of 262. The average age of the population is 33.3 years and, similar to Black Lake, 94% of the population is younger than 65 years. English is considered the mother tongue of 57% of the population, while Dene is the mother tongue for 41% of the population. Approximately 73% of community members are Registered or Treaty Indians.¹⁵³

The main hospital for the region, operated by the Athabasca Health Authority, is located on the border of Chicken 224 Indian Reserve near Stony Rapids.¹⁷ Ultrasound services are currently provided by an itinerant sonographer who visits the Athabasca Health Facility in Stony Rapids approximately one day per month. Patients requiring emergent ultrasound studies generally travel to the communities of Prince Albert or Saskatoon, a driving distance of approximately 903 km and 1,040 km, respectively, from Stony Rapids. Travel to Prince Albert, Saskatoon, or other more southern communities may be via ground transportation (when available via an ice road) or fixed wing, air transportation. Both modes of transportation are limited by availability and weather. Ultrasound services are available at no charge to individuals, with funding provided by the Government of Canada through the First Nations and Inuit Health Branch of Indigenous Services Canada and the Saskatchewan Ministry of Health. Travel costs for patients who must travel outside of their home community for ultrasound imaging are generally covered directly or indirectly through federal funding for Registered Indians; however, travel support for patients' family members to accompany them for ultrasound appointments is only variably provided.

3.3.3 Study participants

Community members were eligible to participate in the study if they had a pregnancy in the past 10 years (as prenatal ultrasound imaging is recognized as part of the standard of care during pregnancy) or if they had required an ultrasound exam as determined by their healthcare provider in the past 10 years, regardless of whether the exam was actually performed, while they resided in a northern Saskatchewan community. Participants were identified and invited to participate by a local advisor in Black Lake who was a member of the project team (M.B.). The local advisor drew upon her personal connections and social networks to invite potential individuals to participate; this was determined to be a culturally safe and culturally relevant approach to participant recruitment and is similar to other projects employing Indigenous methodologies.¹⁴⁷ To ensure participant confidentiality, no medical records or other health information were accessed to identify potential participants. The local advisor did not have a healthcare background, which helped assure participants that their choice of whether or not to participate would not impact their future care. Consistent with interpretive description methodology, a purposive sampling method was used, with consideration given to participant age (to gather a broad spectrum of participant ages), community of residence (residing in either Black Lake or Stony Rapids), and self-identified gender (aiming for representation from all genders and taking into account gender diversity¹⁵⁴).

All participants provided written, informed consent to participate in the study. Care was taken that the advisor and interviewer—who obtained written, informed consent—were not in positions of authority with any of the participants and did not have any relationships with participants which could result in undue influence regarding their choice of whether to participate or not. The study was submitted to the University of Saskatchewan Research Ethics Board (application identification number Beh 17-376) and was determined to be exempt from ethics review. Additionally, the project received support from the Black Lake Denesuline First Nation Band Council as part of a project on improving access to ultrasound imaging using novel technologies.

3.3.4 Data collection

Development of the interview guide was informed through conversations with local healthcare providers. The interview guide was developed by a radiology resident physician (S.A.) in collaboration with a qualitative research specialist (R.T.) and local community advisor

(M.B.). Interviews were conducted by a specialist in qualitative research (R.T.) in collaboration with a local community advisor (M.B.). Interviews were audio recorded if participants consented to audio recording; otherwise, detailed notes were taken during interviews. Participants were also asked to complete a short form requesting demographic information, including information about dates and locations of previous ultrasound exams and previous pregnancies. Interview audio recordings were transcribed and transcripts were reviewed for accuracy. Data analysis was conducted after approximately every five interviews, and participant recruitment continued until data saturation—the point at which no additional thematic categories emerged from recruiting additional participants¹⁵⁵—was achieved. In total, 15 semi-structured interviews were conducted in-person in Stony Rapids and Black Lake.

3.3.5 Data analysis

Transcripts were imported into a software package to store, organize, and analyze data for qualitative and mixed-methods research (NVivo 11, QSR International, Melbourne, Australia). Constant comparative analysis—an analytic method initially developed by Glaser¹⁵⁶ which has subsequently been applied within interpretive description methodology¹⁴⁴—was used to analyse text data. This analytic method comprises a set of systematic procedures relating to coding data and subsequently identifying themes or patterns.^{144,157} Consistent with established procedures, interview transcripts were initially read in their entirety for the researchers to immerse themselves in the data. On subsequent readings of the transcripts, initial codes reflective of key concepts in the transcripts were developed. Relationships between the codes were identified, and codes with common elements were combined into categories.¹⁵⁷ A preliminary coding scheme was developed based on the initial five transcripts. As data collection and analysis continued, data was compared and contrasted between and across individuals, and codes and categories were refined to more accurately represent the data.¹⁵⁷ The analysis was a collaborative effort among a radiology resident physician (S.A.), qualitative research specialist (R.T.), research assistant with training in qualitative research (R.E.), and local community advisor (M.B.). Strategies to ensure analytic rigour included having multiple members of the research team review the initial coding and categorization at multiple time points during the analysis and using an audit trail to trace how codes and categories evolved in subsequent stages of analysis.^{144,158,159}

3.3.6 *Researcher characteristics and reflexivity*

Acknowledging the characteristics of the study's researchers and the perspectives which each bring is a critical aspect of qualitative research methodologies.¹⁶⁰ The research team was diverse and was comprised of two radiologists with health system leadership expertise (P.B. and B.B.), a radiology resident physician (S.A.), a surgeon and expert in virtual care (I.M.), a qualitative research specialist (R.T.), a local Indigenous community advisor (M.B.), and a research assistant with training in qualitative research (R.E.). Researchers' prior experiences—including experience in the provision of healthcare and serving in health system leadership roles in Saskatchewan—were viewed as sources of insight, consistent with interpretive description methodology.¹⁴⁴ All researchers except the local community advisor were external to the community; this allowed them to interpret findings with objectivity, but it is acknowledged that they did not bring lived experience in accessing care in the communities included in the study. All members of the research team—including Indigenous and non-Indigenous members—ensured that culturally safe research methods were employed and findings were interpreted from postcolonial, decolonizing, and Indigenous perspectives. The researchers carefully reflected on their own worldviews and lived experiences, the participants' voices as gathered through interviews, and postcolonial, decolonizing, and Indigenous perspectives which are documented in the literature. The local community advisor helped the research team navigate carrying out the project in a *good way*, bringing lived experience to the diverse range of perspectives which other team members brought to the project.

3.4 Results

3.4.1 *Participant demographics*

Six participants were included on the basis of being pregnant in the past 10 years, and 10 participants were included on the basis of having required a non-obstetrical ultrasound exam in the past 10 years, including one participant who met criteria for both groups. Fourteen females and one male were included. Among those being pregnant in the past 10 years, the mean age (\pm standard deviation [SD]) of participants was 29.7 (± 6.2) years, the mean gravidity (\pm SD) was 3.7 (± 1.9), and the mean parity (\pm SD) was 3.2 (± 1.3). Among those meeting criteria for having a non-obstetrical ultrasound in the past 10 years, the mean age (\pm SD) was 37.7 (± 12.1) years. Indications for non-obstetrical ultrasound studies were right upper quadrant pain / assess for

gallbladder pathology (n = 4), pelvic pain (n = 3), assess for the presence of renal calculi (n=1), assess hernia (n = 1), and vaginal bleeding (n = 1).

3.4.2 Themes

Five themes were identified from semi-structured interviews: geographic isolation from imaging facilities, (not) adapting in the face of remoteness from ultrasound imaging facilities, competing responsibilities of family and work, ultrasound as a tool towards understanding disease and securing optimal health outcomes, and the importance placed on imaging services near one's community.

3.4.2.1 Geographic isolation from ultrasound imaging facilities

Geographic isolation was seen as an ever-present factor which most participants were accustomed to, but which directly impacted their way of life, including when accessing imaging. Participants were acutely aware of the geographic isolation of their communities; as one participant noted, "It's so isolated up here, up north." Another participant commented on the degree of remoteness of her community in comparison to communities classified as rural: "Those small farm towns, they can go to Regina [a major city in the province]. Well, here you got to go all the way to La Ronge, P.A. [smaller centres 664 km and 903 km away]." Some participants connected geographic isolation to the lack of availability of imaging and other healthcare technologies; for example, a participant noted, "we all are isolated to all the modern technologies that a hospital and facilities down south can be equipped with." For some, this resulted in a sense of vulnerability: "I think because we have less services like the people do in the cities, you know, you never know what kind of a medical situation we are in."

3.4.2.2 (Not) adapting in the face of remoteness from ultrasound imaging facilities

Participants commonly had to either wait for an itinerant sonographer to come to their community generally once each month or travel to a larger community for ultrasound imaging (provided that travel costs were approved for federal funding). Challenges associated with travelling to another community for imaging included fear of travel, isolation from family and unfamiliarity with the city, financial challenges, inadequacy of accommodations, and feelings of guilt. These sub-themes are discussed below.

Wait times. Wait times for ultrasound exams was one of the most salient features about their ultrasound exam experience which participants recalled, including wait times for the day of the ultrasound exam and wait times at the clinic on the day of the exam. Wait times for an

ultrasound exam ranged from a few days to a year. One participant noted that even though she was scheduled for an ultrasound exam on a specific date, because of the volume of exams to be performed the day the itinerant sonographer was at the facility, the exam had to be rescheduled for the following month. While waiting for the exam, some residents described feeling anxious, while others felt it was “okay”. The long wait times also led to a sense of unfairness by some residents: “Like why do we have to be on a waiting list? Wait until we die or what? You know? ... It’s like we’re left behind. What do you call that again? We’re just like ignored or whatnot.”

Fear of travel. A fear of air travel was shared by many participants and deterred some participants from travelling for an ultrasound exam. A plane crash resulting in a fatality in the six months preceding the interviews remained on participants’ minds, and there was a general desire for residents to have their healthcare needs met locally. Sometimes the fear of flying led participants to find other means of travelling to their appointments such as driving, even if the trip took 12 or 14 hours.

Participants often missed their ultrasound appointments due to weather impeding flights to southern communities. In some cases the challenges associated with rescheduling the appointment led residents to forego the ultrasound exam altogether. One participant noted, “So I thought they were automatically going to reset [reschedule the exam]. But I had to go through the whole process again for them to remake an appointment. I didn't even bother.”

Isolation from family and unfamiliarity with the city. Some obstetrical participants wanted to share the experience of having an ultrasound exam with their partner, but because of the need to travel and travel costs not being covered for their partner, found this was not possible:

And I was always alone going – I was told that I couldn’t bring my partner with me at the time to see the ultrasound. I don’t know why because it was some transportation thing they had to pay for. I don’t know. ... all those three ultrasounds I went to I was there alone. [I felt] pretty upset because it was my first time pregnancy and it’d be nice for my partner to be there and actually hear the heart beat the first time and all that, yeah. I was pretty upset about that.

A larger city was an unfamiliar or strange place for many participants who had lived in a northern community their entire life. For obstetrical patients especially at a younger age, going alone to a larger city was sometimes a frightening experience: “[The ultrasound exam] was in Saskatoon and I was just 18 so I never really travelled out alone that far so I was kind of scared.

And my mom was so concerned about me when I went... And then after my ultrasound they didn't tell me anything of what was going on with me; they just made me go back here."

However, for others, the opportunity to travel to the city for an ultrasound exam meant that other tasks such as shopping could be done at the same time: "And there's some people that want to go down south because they get to go shopping. I'll be honest with you. Like when I went, I said, "Oh great! I'll get some things done. I got to go to this, I got to go get this."

Financial challenges and inadequacy of accommodations. While the cost of ultrasound exams and travel costs were generally covered by federal funding, participants found difficulty managing additional costs, for example related to snacks and some meals, when they were travelling. One participant reflected, "With people with medical conditions such as diabetic or gestational, if they don't have any money and they'll be sent out on a medical and some they might faint or something like that. And they won't have any money for – like right after the appointment they don't have nothing to eat right away like if they don't have money."

Depending on the time of their appointment, some patients stayed overnight in a hotel room provided through federal funding. However, these accommodations were often substandard: "But the accommodations were just gross, awful places to stay waiting for appointments and whatnot. ... You know. ... Who wants to stay in a dingy hotel like that, you know? When you live up here in a comfortable home where you feel at home, it's just awful."

Feelings of guilt. One participant described having felt guilty about having to expend government resources on travel for health services, resulting in delaying care: "For years of living here I felt guilty letting somebody else pay my way to P.A. [a city which has regular ultrasound services]. But that's my treaty right. For years I'd just wait until I get to Regina to take care of my physical health needs. Because I felt guilty saying I need to go and have them pay."

3.4.2.3 Competing responsibilities of family and work

Having children who needed their care was a barrier for many participants to attend an ultrasound appointment. Participants noted that it was common to miss appointments if childcare was not available: "It [local ultrasound exams] would be better than traveling down south...cause you have to stay away from your family while going for appointments and some people don't have babysitters... Cause a lot of people miss their appointments down south." In contrast,

travelling south for an ultrasound exam was a different experience for participants who did not have children. For example, one participant noted, “I didn’t mind. Cause me, I don’t have kids.”

Work responsibilities were also identified as barriers to accessing ultrasound exams, as travelling to a larger city often meant missing multiple days of work. One participant shared, “If it’s here in Stony it’s reasonable. Cause I work throughout Stony and I could just go over there and then I could see my supervisor. If I’m telling her that I’m going down south there will be like, stuff I can’t go. Like missing days, and if it’s like emergency and it’s too last minute, I have to tell her two weeks ahead of time.”

3.4.2.4 Ultrasound as a tool towards understanding disease and securing optimal health outcomes

Medical obligation. Residents considered going for an ultrasound exam as an obligation and a priority despite the many challenges associated with access. For example, one participant noted, “Well it takes long but still I have to be there for my health.” Another participant commented, “But no choice, eh? You’ve got to go for your medical appointments, so I had to go because I got really sick from my last gallstones.” One participant equated ultrasound imaging to a lifesaving technology: “Ultrasound is really good. It’s saved lots of people. It saves lots of babies too. ... You know, like that [ultrasound exam] saved her, you know? Ultrasound saved [name de-identified].”

Diagnostic information to inform and empower patients. Participants placed high importance on the need for ultrasound exams, especially obstetrical exams to monitor fetal development. Ultrasound was also seen as a tool for reassurance: “[The ultrasound exam] was pretty important. I wanted to actually follow-up and do a [follow-up exam] – see if my son was in a healthy – you know?”

Diagnostic information provided by ultrasound imaging was valued by patients and seen as a tool to help them understand their health and disease: “I think...ultrasound is good because it helps them [patients] to understand. It helps them where they are, you know, if something – they want to know something is wrong with them, hey? That’s what they’re there for. ... We deserve to know what’s going on in our bodies I guess, right?”

Need for patient education. Despite the general acceptance and importance placed on imaging, some participants expressed concerns regarding radiation risks that they associated with ultrasound imaging, suggesting that further education about the safety and risks associated with

medical imaging may be helpful: “But people are concerned about that radioactive kind of thing.... If you get more and more and more ultrasound of different in I don’t know how many years or months, they pick that up and it builds in the body and people they get cancer or get sick.”

3.4.2.5 Importance placed on ultrasound services near one’s community

Participants indicated that having ultrasound services near one’s community was important, and commented that locally available ultrasound services may mitigate some of the challenges previously identified such as childcare, fear of travel, the time associated with travel to a southern community, and costs to the healthcare system. One participant reflected, “Because probably there’s other patients that would actually [go for a local ultrasound exam] – [they] don’t want to go [south] and they have no babysitters and so whatever and they don’t have time to actually go south for it. They could just always go to Stony Hospital and just get it done there.” Participants also stressed the importance of imaging from someone who “knows”—the ability to receive care from a specialist in one of the larger cities.

3.5 Discussion

This study provides a richer understanding of perceptions of access, and factors which shape access, to ultrasound imaging among northern, remote, Indigenous community members in Canada, demonstrating significant disparities in access to ultrasound imaging services. Geographic isolation from centrally situated ultrasound imaging facilities was a central barrier for northern residents to access prenatal and general diagnostic ultrasound. Large geographic separation from ultrasound imaging facilities and the increased time required for travel exacerbated other barriers, including fear of air travel, isolation from family, financial means, and unfamiliarity with larger cities. Additional barriers, such as family and work responsibilities, were exacerbated by the barrier of geographic isolation. Compared to urban areas in which childcare may be required for only two hours during an appointment, an ultrasound appointment for a northern resident resulted in the need for childcare for a full day or multiple days. Residents overcame these barriers as they were motivated by potential diagnostic benefits of ultrasound imaging, and ultrasound imaging provided reassurance about the health of their baby.

In addition to Levesque et al.’s framework of access to care which provides a theoretical grounding for this study, a number of other frameworks of access have been described in the

literature. Among the dominant theories of healthcare access is one described by Penchansky and Thomas in 1981; in their framework, access consists of the five dimensions of availability, accessibility, accommodation, affordability, and acceptability.⁴⁵ Other researchers have conceptualized access in a similar manner. Peters et al. describe dimensions of access as quality, geographic accessibility, availability, financial accessibility, and acceptability of services,⁴⁶ and Shengelia et al. describe physical access, resource availability, cultural acceptability, financial affordability, adherence, and quality of care as concepts representing effective health coverage and the health service provision function.⁴⁷ More recently, drawing upon the work of Penchansky and Thomas and others, Levesque et al.'s framework⁴⁸ uniquely describes five dimensions of accessibility which interact with five corresponding abilities of populations. This results in an attractive theoretical framework to understand and conceptualize access from both health system and patient perspectives. Postcolonial, decolonizing, and Indigenizing perspectives on health system access—which emphasize the social, historical, and political contexts of healthcare, access as a social responsibility and a social relationship, and a holistic approach to health and well-being—are also critical in understanding the challenge of access to ultrasound in northern, remote, Indigenous communities.^{19,148–151}

Drawing upon Levesque et al.'s conceptualization of access to care, disparities in specific dimensions of accessibility—including availability, appropriateness, acceptability, approachability, and affordability—contributed to limited access to ultrasound imaging for patients in the two northern, remote, Indigenous communities studied. As the itinerant sonographer model provided ultrasound services only one day each month, availability of ultrasound imaging was significantly limited, and patients often had to travel long distances for ultrasound imaging for urgent exams or if wait times were too long. Participants described a myriad of concerns regarding appropriateness of services, which is thought of as the “fit between services and clients need”.⁴⁸ These concerns ranged from long wait times, unfavorable policies regarding funding for family members or partners to travel with them for an appointment, and inadequate hotel accommodations when travelling for an appointment, which together worked to limit access to ultrasound imaging.

The acceptability of ultrasound services, another dimension of accessibility related to cultural and social factors of the population,⁴⁸ is particularly important to consider in this largely Indigenous population. Many Indigenous cultures consider pregnancy to be a natural process

maintained by nature and requiring no interference.¹⁶¹ While ultrasound is a Western concept outside of traditional Indigenous medicine, in this study it was observed that ultrasound had become integrated into the norms of prenatal care for Indigenous mothers. This is a significant finding, as perceptions that healthcare is inadequate or not culturally appropriate are barriers for many Indigenous persons in seeking care.⁸ Ultrasound—both obstetrical ultrasound and general diagnostic non-obstetrical ultrasound—could be considered as contributing to a pursuit towards holistic health in terms of understanding one's health, providing reassurance about the health of one's baby (thereby promoting mental well-being), and ensuring one's physical health is maintained or repaired (thereby promoting physical well-being).

Holistic health and well-being, including the interaction between mental, emotional, and spiritual stress and physical health, are important when considering the acceptability of ultrasound services for Indigenous peoples.¹⁵¹ Although an ultrasound exam may be considered a tool to help patients achieve mental and physical well-being as described above, the process of obtaining an ultrasound exam has the potential to diminish holistic health and well-being, as exemplified in our study by the emotional hardships of a young patient traveling alone for an ultrasound exam without her family. Indigenous peoples' negative experiences in the healthcare system may lead some to not proceed with care, as one participant explained in our study. A sense of unfairness about wait times for an ultrasound exam expressed by participants may reflect historical legacies associated with healthcare services for Indigenous peoples. Health disparities secondary to colonial legacies have been documented in Canada as well as other countries such as Australia, New Zealand, and the United States, with colonization adversely affecting physical, social, emotional, and mental health and well-being of Indigenous peoples.¹⁶² It is critical for health systems to ensure cultural safety throughout the planning, delivery, and evaluation of medical imaging services in a way which supports Indigenous peoples' needs and fosters ethical and respectful relationships between patients and providers.^{163,164}

Affordability and approachability—the final two dimensions of accessibility in Levesque et al.'s framework—featured less prominently in the narratives of study participants. The universal health system in Canada which allows all Canadians to receive publicly funded ultrasound services without patient payment, as well as funding for travel and accommodations for medical appointments for Registered Indians, worked together to contribute to achieving accessibility for Indigenous patients. However, patient-related costs such as loss of employment

income and cost of meals during travel should be acknowledged. Approachability, which relates to services “mak[ing] themselves more or less known among various social or geographical population groups”,⁴⁸ was slightly diminished as exemplified by participants’ cancelled appointments not automatically being rebooked. However, relative to other dimensions of accessibility, approachability featured less prominently in participants’ narratives, possibly because all the interview participants had previous personal experience with having an ultrasound exam.

Despite many factors which limited *accessibility* to ultrasound services, the five corresponding abilities of populations which interact with the dimensions of accessibility in Levesque et al.’s framework, including the ability to perceive, ability to seek, ability to engage, ability to reach, and ability to pay, helped generate some degree of *access* to ultrasound services. Participants had a strong understanding of the benefits of ultrasound imaging and perceived a clear need for ultrasound exams. Participants sought ultrasound exams as they were consistent with their personal and cultural values. This contributed to participants’ abilities to seek and engage in ultrasound imaging, requirements for creating access according to Levesque et al.’s framework.⁴⁸ Borrowing terminology proposed by Frenk, despite the many obstacles to accessing imaging (“resistance” imposed by systemic and social barriers), many participants overcame these obstacles (“utilization power”).¹³⁷ However, exceptions should be noted, and it must be recognized that some participants chose not to proceed with their ultrasound exam due to personal or administrative barriers (e.g. work concerns, childcare needs, or appointments cancelled due to weather). These barriers compromised individuals’ ability to reach ultrasound imaging and resulted in missed opportunities to provide imaging, with uncertain consequences on health status. The final corresponding ability in Levesque’s model, the ability to pay, was less prominent in participants’ narratives as a barrier to accessing ultrasound imaging due to the universal coverage of medically necessary ultrasound exams in Canada’s healthcare system, though was highlighted as a challenge when patients traveled for an ultrasound exam.

This study identified geographic isolation as a central barrier to accessing ultrasound imaging. The importance of geography in promoting or hindering access to imaging is a finding that is a key theme in the literature, particularly among marginalized or underserved populations. In a systematic review of the literature regarding healthcare access and utilization among Indigenous peoples in North America, Australia and New Zealand, rural location—along with

communication and socioeconomic status—was a barrier to healthcare services that disproportionately affected Indigenous communities.¹³⁰ In a study exploring travel time to mammography, breast ultrasound, and breast magnetic resonance imaging (MRI), Native American women in the United States had median travel times 2-3 times longer than women of other racial/ethnic groups.¹⁶⁵ Additionally, in the context of lung cancer screening in the United States, census tracts which had relatively greater distances to computed tomography (CT) facilities had higher proportions of uninsured patients, Medicaid patients, and undereducated patients (less than a high school degree).¹⁶⁶

This study points toward the need for increased availability of local ultrasound services and new solutions which overcome challenges associated with geographic dispersion of a population in small communities over a large territory. One of those solutions may be telerobotic ultrasound, a technology which allows sonographers or radiologists to remotely manipulate an ultrasound probe from a central site (such as an urban ultrasound clinic or hospital).^{5,54,167} Using this technology, patients can stay in their home community while receiving imaging care from sonographers and radiologists. This technology was recently used by our group to provide critical ultrasound services during the COVID-19 pandemic in a northern Canadian community.¹⁶⁸ Benefits of providing ultrasound services using this technology included eliminating the need to travel, increased availability of ultrasound services (including availability for emergencies and decreased wait times for exams), increased convenience, and increased safety—particularly prominent during the COVID-19 pandemic.¹⁶⁸ These benefits closely align with the dimensions of availability and acceptability in Levesque et al.'s framework.

Other potential solutions to address some of the barriers identified in this study include proactively reaching out to patients to re-book cancelled or missed exams, providing solutions to facilitate childcare during appointments, and providing extended hours for patients with family and work responsibilities. Policies should consider the personal and bonding benefits of obstetrical ultrasound imaging and ensure patients' partners are welcome to participate in the experience of an ultrasound exam. Reaching out to patients who missed their appointments to identify and help resolve any barriers which stand in the way of undertaking their imaging exam may also help improve access to ultrasound services. These solutions may be broadly applicable across radiology practices to increase access to imaging. In addition, Brooks-Cleator et al. identified six key elements of culturally safe health initiatives: collaboration and partnerships

with members of Indigenous communities; acknowledging power dynamics and empowering patients; addressing the broader context of patients' lives; creating safe environments which are non-judgmental, free from racism and stereotyping, and supportive of Indigenous cultures; organizational and individual level self-reflection on personal biases and those of the health system; and cultural safety and cultural competency training for healthcare providers.¹⁶⁴ These may be important strategies for radiology practices and health systems to consider to ensure cultural safety and increase access to imaging for Indigenous peoples.

There are a few limitations to this study. All participants were from only two northern, remote, Indigenous communities. While this approach provided rich and focused data to describe access to ultrasound services in its many dimensions in these two communities, findings may not be generalizable to other northern communities in Canada or beyond. Although the interviewer was external to the local health authority, social desirability bias and perceived power differentials may have manifested in some participants being reluctant to speak negatively about current services or provide detailed responses about their experiences.¹⁶⁹ As the interviewer was not from either of the northern, remote communities, participants may have expressed their thoughts in a way which they felt would best be accepted by the interviewer. Additionally, while there have been few policy changes related to ultrasound imaging in the two northern communities over the study period, the relatively long period of time since some participants may have had previous ultrasound exams may distort participants' recollections of past experiences of ultrasound imaging.¹⁷⁰ This study explores the concept of access to ultrasound imaging as "the opportunity to reach and obtain appropriate health care services in situations of perceived need for care".⁴⁸ It does not, however, explore the concept of utilization, and does not explore whether access to imaging affects utilization, defined as "the quantity of health care services and procedures used".⁴⁷ Further, while the perspectives of patients and community members are presented in this study, the study does not include the potentially different perspectives of healthcare administrators, physicians, or other healthcare providers in describing access to ultrasound imaging. The design of this study emphasizes the importance of patients' voices in defining access to ultrasound imaging, and is consistent with principles of patient- and family-centred care and Indigenous health research in that the perspective of patients and the community is of primary importance.

3.6 Conclusion

In conclusion, this study highlights disparities in access to ultrasound imaging—a core imaging modality—for northern, remote, Indigenous populations. As shared through the narratives of interview participants, this study emphasizes the importance of regularly available local ultrasound services to meet patients’ needs, and suggests that future efforts to improve access to imaging should consider barriers of distance to imaging facilities and strategies to bridge these barriers. As healthcare leaders focus on patient- and family-centered care, cultural safety, and improving patient experience, it will be increasingly important to focus on access to imaging and its multi-dimensional conceptualization.

3.7 Acknowledgements

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CHAPTER 4

SOCIODEMOGRAPHIC AND GEOGRAPHIC DISPARITIES IN OBSTETRICAL ULTRASOUND IMAGING UTILIZATION: A POPULATION-BASED STUDY*

The previous chapter provided key insights into factors which shape access to ultrasound imaging for northern, remote, Indigenous populations in the context of a multidimensional framework. As Chapter 3 highlighted many barriers which northern, remote, Indigenous peoples face, including most prominently geographic remoteness from ultrasound facilities, a key question is whether these barriers to *access* ultrasound imaging result in disparities in ultrasound imaging *utilization*. Chapter 4 presents a population-based study to assess the association between sociodemographic and geographic factors and obstetrical ultrasound utilization, an important aspect of prenatal care. The study's findings are important from a health policy perspective, providing a call to policy makers that targeted efforts to reduce inequities in obstetrical ultrasound imaging utilization are required to ensure equitable opportunity for all pregnant women to receive obstetrical imaging.

* This chapter is based on:
Adams SJ, Yao S, Mondal P, Lim H, Mendez I, Babyn P. Sociodemographic and geographic disparities in obstetrical ultrasound imaging utilization: a population-based study. *Acad Radiol*. 2021. doi: 10.1016/j.acra.2021.07.012 (online ahead of print)

4.1 Abstract

Rationale and Objectives: Obstetrical ultrasound imaging is an important part of prenatal care, though not all patients have readily available access to ultrasound services. This study aimed to assess the association between sociodemographic and geographic factors and (1) having a second trimester complete obstetrical ultrasound and (2) overall obstetrical ultrasound utilization.

Methods: All pregnancies and obstetrical ultrasound exams billed from 2014-2018 in Saskatchewan, Canada were identified from province-wide databases. Generalized estimating equation (GEE) models with binomial and Poisson distributions were used to identify factors associated with having a second trimester ultrasound and overall obstetrical ultrasound utilization, respectively.

Results: 80,536 pregnancies from 57,881 individuals were included. Of 57,186 pregnancies carried to ≥ 23 weeks, a second trimester ultrasound was performed in 50,180 (87.7%). Patients living in rural areas (adjusted odds ratio [aOR], 0.70; 95% confidence interval [CI], 0.63-0.77; $p < 0.0001$), remote areas (aOR, 0.35 for greatest vs. least remoteness level; 95% CI, 0.32-0.39; $p < 0.0001$), and status First Nations individuals (aOR, 0.50; 95% CI, 0.46-0.53; $p < 0.0001$) were less likely to have a second trimester ultrasound. Patients living in higher income neighbourhoods (aOR, 1.86 for highest vs. lowest quintile; 95% CI, 1.62-2.13; $p < 0.0001$) were more likely to have a second trimester ultrasound. GEE Poisson regression analysis demonstrated these same factors, except rural residence, were associated with overall obstetrical ultrasound utilization.

Conclusion: Substantial disparities in obstetrical ultrasound utilization exist among patients in remote geographic areas, Indigenous peoples, and patients in low income neighbourhoods. Addressing barriers which these demographic groups face in accessing ultrasound imaging is critical to ensure health equity.

4.2 Introduction

Ultrasound imaging is an important component of prenatal care to predict adverse pregnancy events, inform obstetrical management, and improve pregnancy outcomes.¹³⁵ Despite the importance of obstetrical ultrasound imaging in prenatal care, access to obstetrical ultrasound is limited for many patients across North America.^{1,138} Access is particularly limited for women

in rural and remote communities, where the closest facility to offer ultrasound services may be hundreds of kilometres away.¹³⁸ Our previous research found that geographic isolation from ultrasound facilities was a central barrier for patients in northern, remote, Indigenous communities to access ultrasound imaging.¹⁷¹ Other barriers to accessing ultrasound imaging, such as competing family and work responsibilities, were exacerbated by geographic distance from ultrasound imaging facilities and the increased time required to travel to an ultrasound facility.¹⁷¹ As a high proportion of patients in remote communities are Indigenous, these barriers disproportionately impact Indigenous peoples, who face multiple barriers to accessing healthcare services.⁴

Distinction must be made between *access* to ultrasound services, which has been defined as “the opportunity to reach and obtain appropriate health care services in situations of perceived need for care”⁴⁸, and *utilization* of ultrasound services, which can be thought of as “realized access.”¹²⁹ The relationship between access and utilization is complex, and based on a dominant theoretical paradigm, predicting and explaining imaging utilization relies on understanding individuals’ predisposition to use services, factors which enable or impede use (such as availability of ultrasound facilities), and individuals’ need for care.¹⁷²

Research investigating sociodemographic and geographic factors associated with obstetrical ultrasound utilization is limited, though a number of studies have investigated factors associated with prenatal care utilization in general. Younger maternal age, lower socioeconomic status (including lower income and education level), Indigenous ancestry, immigration status, multiparity, and substance use have each been shown to be associated with lower rates of prenatal care.^{173–177}

Despite increased recognition of the importance of exploring and addressing healthcare disparities in other specialties, there are relatively few papers in the radiological literature exploring health care disparities, and there have been calls for radiology to focus on research and curricula in healthcare disparities.¹⁷⁸ Identification of specific demographic groups with decreased rates of obstetrical ultrasound imaging is critical to identify disparities in guideline-recommended obstetrical care in health systems. Such findings may inform approaches to improve access to obstetrical ultrasound for specific demographic groups and thereby ensure equitable opportunity for all pregnant women to receive obstetrical imaging, including second trimester obstetrical ultrasound exams which are considered standard of care.¹³⁶ Thus, the

objective of this study was to assess the association between sociodemographic and geographic factors and (1) having a second trimester complete obstetrical ultrasound exam during a pregnancy, which is recommended that all pregnant women be offered between 18 and 22 weeks' gestation¹³⁶ and (2) overall obstetrical ultrasound utilization. Based on empirical findings in the literature^{4,173–177} and theoretical frameworks of healthcare utilization,^{172,179} we hypothesized that due to structural barriers, specific demographic groups, including Indigenous patients, patients in rural communities, and patients with increased remoteness from major centres, would be less likely to have a second trimester complete obstetrical ultrasound exam and have lower rates of obstetrical ultrasound imaging utilization.

4.3 Methods

4.3.1 Study cohort

A population-based study was undertaken in the province of Saskatchewan, Canada. The research protocol was submitted to the University of Saskatchewan Research Ethics Board and was deemed to be exempt from research ethics review and approval.

Inclusion criteria were (1) women registered for medical services in the province of Saskatchewan, Canada at any time between January 1, 2014 and December 31, 2018 (the “study period”) and (2) women who had at least one pregnancy with the date of the first day of the last menstrual period (LMP) and the date of delivery or abortion both within the study period. Data for women with multiple pregnancies were documented separately for each pregnancy. From this cohort, a sub-cohort of pregnancies carried to at least 23 weeks was defined to identify sociodemographic and geographic factors associated with having specifically a second trimester complete obstetrical ultrasound exam, which is recommended between 18 and 22 weeks' gestation.¹³⁶ Pregnancies with the first day of the LMP or date of delivery outside of the study period and pregnancies in women who relocated to another province or country during their pregnancy were excluded. All women included in the cohort were identified by querying the provincial Discharge Abstract Database and Ministry of Health Medical Services Branch physician billing data for diagnosis and procedure codes associated with pregnancy as previously described.¹⁸⁰

4.3.2 Explanatory and outcome variables

4.3.2.1 Explanatory variables

Variables were selected for inclusion based on theoretical models of healthcare utilization (e.g. Andersen's Behavioral Model of Health Services Use) and prior literature exploring sociodemographic and geographic factors associated with prenatal care utilization in general.^{172–177,179} Demographic information, including maternal age and First Nations status, was abstracted from the Personal Health Registration System. Maternal age was defined at the time of the estimated first day of the LMP for each pregnancy. First Nations status is self-declared by First Nations persons registered under the *Indian Act*.

The Obstetric Comorbidity Index was used as a proxy for maternal health status,^{181,182} and was calculated for each individual based on ICD-10-CA diagnosis codes from the Discharge Abstract Database. Additional health information, including the number of pregnancies (gravidity), number of past deliveries (parity), and pregnancy outcomes, were also determined based on ICD-10-CA codes from the Discharge Abstract Database.

As a proxy for geographic remoteness, an index of remoteness was determined for each individual based on the census subdivision (CSD—a municipality or an area equivalent to a municipality for statistical reporting purposes) of each individual's physical address as available within the Personal Health Registration System at the beginning of each pregnancy. This index of remoteness, publicly released by Statistics Canada in 2020, is based on (1) the proximity of a CSD to all population centres within a given radius that permits daily accessibility and (2) the population size of each population centre to reflect general service availability within that population centre.^{183,184} Travel cost, rather than network distance or travel time, was used as a common measure of “distance” to account for communities with various transportation infrastructures. The index of remoteness is a continuous variable scaled from 0 (least remote) to 1 (most remote) and demonstrates high correlation to accessibility measures specific to healthcare services.¹⁸⁴ As the two largest cities in the province, Saskatoon and Regina, both had index of remoteness values slightly less than 0.23, an index of remoteness level of <0.23 was chosen as the reference category for subsequent analyses.

In addition, urban vs. rural status was assigned for each individual based on residence location at the beginning of each pregnancy as indicated in the Personal Health Registration System. Urban was defined as comprising all population centres, defined by Statistics Canada as

a defined geographic unit with a population of at least 1,000 and a population density of 400 persons or more per square kilometre population.¹⁸⁵ Rural was defined as all territory lying outside population centres (urban centres).¹⁸⁶

Neighbourhood income quintile was used as a proxy for socioeconomic status, similar to prior studies.^{187–189} Dissemination area, the smallest geographical unit available for analysis in the Canadian census, was extracted for each individual based on their residence at the beginning of each pregnancy. Neighbourhood income quintiles for each dissemination area were based on average income per single person equivalent and based on data from the 2011 Census as previously described.¹⁹⁰ The neighbourhood income quintile of each individual's respective dissemination area was assigned to each individual.¹⁹⁰ Based on data limitations of the Personal Health Registration System, data for urban vs. rural status and neighbourhood income quintile were available only from January 2014 to October 2017.

4.3.2.1 Outcome variables

Ultrasound exams were abstracted from (1) the provincial Radiology Information System (RIS), which captures all ultrasound exams performed in public facilities in the province, and (2) provincial Ministry of Health Medical Services Branch (MSB) physician billing data, which captures all ultrasound exams performed in private facilities in the province. Together, these two data sources capture all formal diagnostic ultrasound exams billed in the province.

Obstetrical ultrasound exams were identified in RIS and MSB physician billing data through a query of exam codes indicating a first trimester ultrasound exam, second trimester ultrasound exam, third trimester ultrasound exam, obstetrical ultrasound exam with trimester not specified, and biophysical profile. In cases where the exam code did not specify the trimester, the trimester was estimated based on estimated gestational age as determined through the Discharge Abstract Database. Nuchal translucency exams and amniocenteses were excluded. All obstetrical ultrasound exams performed on the same day (e.g. transabdominal and transvaginal exams coded with two separate exam codes) were counted as a single exam. The performance of a second trimester complete obstetrical exam, as well as the total number of obstetrical exams performed during each pregnancy, was determined.

4.3.3 Statistical analysis

Descriptive statistics, including means (\pm standard deviation) for continuous variables and frequencies (%) for categorical variables, were used to summarize population demographic characteristics and obstetrical ultrasound exam count data.

4.3.3.1 Second trimester obstetrical ultrasound utilization

In the sub-cohort of women with pregnancies carried to at least 23 weeks' gestation, the number and proportion of women who had a second trimester obstetrical ultrasound exam were determined for each stratum of each explanatory variable. Univariate logistic regression was used to evaluate odds ratios (ORs) and 95% confidence intervals (CIs) for each predictor in a generalized estimating equation (GEE) model.

Variables from univariate analysis with $p < 0.20$ were considered for inclusion in a multivariate GEE logistic regression model using stepwise selection. Odds ratios and adjusted odds ratios (aORs) and 95% CIs were estimated. Multicollinearity among independent variables was assessed using variance inflation factors and interactions between covariates were examined. Additionally, aORs of having a second trimester obstetrical ultrasound exam were estimated for each census division and medium and large population centre in Saskatchewan and were visually represented on a choropleth map with a color progression used to represent different aOR values.

4.3.3.2 Overall obstetrical ultrasound utilization

The total numbers of obstetrical ultrasound exams performed during each pregnancy within each stratum of each variable were represented as incidence rate ratios (IRRs), and GEE Poisson regression modeling was used to identify significant variables.

Variables from univariate analysis with $p < 0.20$ were considered for inclusion in a multivariate GEE Poisson regression model using stepwise selection to identify sociodemographic and geographic factors which were associated with the total number of obstetrical ultrasound exams performed during each pregnancy. Gestational age at the time of delivery was included as an offset variable to account for increased potential for additional ultrasound exams as gestational age increases. Interactions between covariates were examined. Multicollinearity among independent variables was assessed using variance inflation factors. Adjusted incident rate ratios (aIRRs) were estimated for each census division and medium and large population centre in Saskatchewan and were represented on a choropleth map.

Significance level (α) was set at 0.05 for all analyses. Statistical analyses were performed with SAS, version 9.4 (SAS Institute, Cary, NC). Choropleth maps were created using MapInfo Pro 2019 (Precisely, Pearl River, New York).

4.4 Results

4.4.1 Population characteristics

A total of 655,770 women were registered for medical services during the study period, and of these individuals, 57,881 (8.9%) had at least one pregnancy with the estimated first day of the LMP and delivery date both during the study period (Figure 4.1). As some individuals had multiple pregnancies during the study period, a total of 80,536 pregnancies were identified. Of these, 57,186 pregnancies were carried to at least 23 weeks' gestational age. Population characteristics are summarized in Table 4.1.

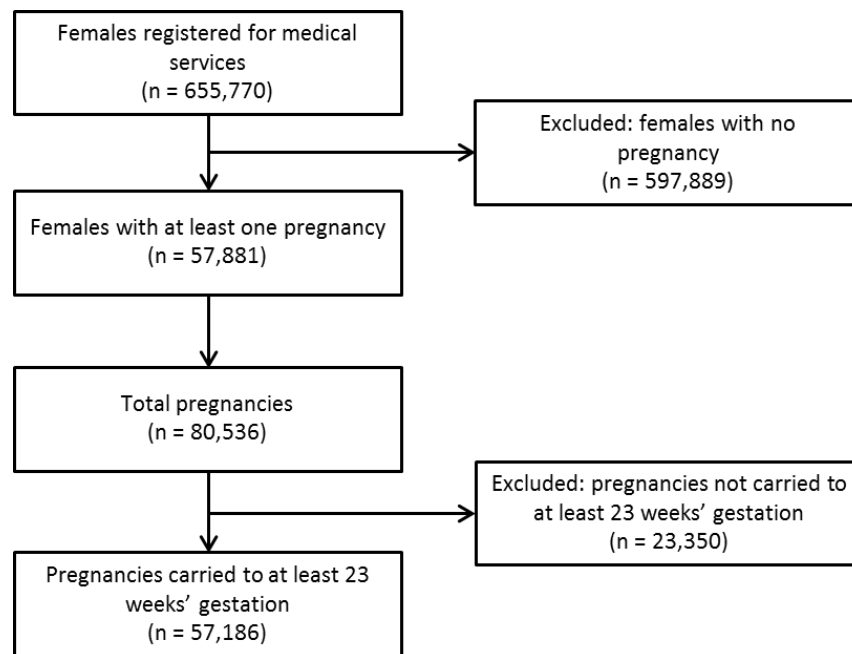


Figure 4.1. Flowchart of the study population. The study cohort was identified from the Saskatchewan Personal Health Registration System, which includes all individuals registered for medical services in Saskatchewan, Canada, during the study period (January 1, 2014 and December 31, 2018).

Table 4.1. Population characteristics

	For each unique individual (n = 57,881)	For each pregnancy within the study period (n = 80,536)*
Years of follow-up data available per individual during the 5 year study period, mean (\pm SD)	4.8 (\pm 0.5)	
Pregnancies during the study period, n (%)		
1	40,000 (69%)	
2	14,010 (24%)	
≥ 3	3,871 (7%)	
Status First Nations, n (%)		
Yes	11,592 (20%)	
No	46,289 (80%)	
Maternal age at the beginning of pregnancy, mean (\pm SD)		28.1 (\pm 5.8)
Gestational age at the time of delivery in weeks, mean (\pm SD)		30.8 (\pm 13.2)
Pregnancy outcome, n (%)		
Live birth		56,869 (71%)
Stillbirth		424 (1%)
Spontaneous abortion		13,904 (17%)
Induced abortion		9,301 (12%)
Birth type mixed or unspecified		38 (0%)
Gravidity, n (%)		
1		29,609 (37%)
2		21,380 (27%)
3		12,855 (16%)
≥ 4		16,692 (21%)
Parity, n (%)		
0		57,099 (71%)
1		12,671 (16%)
2		5,683 (7%)
≥ 3		5,083 (6%)
Obstetric Comorbidity Index, n (%)		
0		50,099 (62%)
1-2		5,847 (7%)
3-4		15,389 (19%)
≥ 5		9,201 (11%)
Location of residence, n (%)		
Urban		50,747 (63%)
Rural		7,597 (9%)
Missing		22,192 (28%)

Index of remoteness, n (%)	
<0.23	35,794 (44%)
0.23-0.30	18,168 (23%)
0.31-0.40	15,675 (19%)
≥0.41	10,395 (13%)
Missing	504 (1%)
Neighbourhood income quintile, n (%)	
1 (lowest)	13,865 (17%)
2	11,214 (14%)
3	10,226 (13%)
4	11,174 (14%)
5 (highest)	7,993 (10%)
Missing	26,064 (32%)

* Across all pregnancy outcomes (live birth, stillbirth, spontaneous abortion, and induced abortion).

SD, standard deviation.

4.4.2 Predictors of having a second trimester complete ultrasound exam

In the sub-cohort of pregnancies carried to at least 23 weeks' gestation, a second trimester complete obstetrical ultrasound was performed during 50,180 (87.7%) pregnancies. In univariate analyses, maternal age, First Nations status, gravidity, parity, Obstetric Comorbidity Index, urban vs. rural residence, index of remoteness, and neighbourhood income quintile were statistically significant factors associated with having a second trimester obstetrical ultrasound performed (all $p < 0.0001$) and were included in the multivariate model.

In the multivariate GEE model, advanced maternal age was associated with being more likely to have a second trimester obstetrical ultrasound exam (aOR, 1.03 for each 1 year increase in age; 95% CI, 1.03-1.04; $p < 0.0001$). Individuals who were status First Nations (aOR, 0.50; 95% CI, 0.46-0.53; $p < 0.0001$), had higher parity (aOR, 0.44 for parity ≥ 3 vs. 1; 95% CI, 0.37-0.52; $p < 0.0001$), lived in a rural area (aOR, 0.70; 95% CI, 0.63-0.77; $p < 0.0001$), and lived in a more remote area (aOR, 0.35 for index of remoteness ≥ 0.41 vs. < 0.23 ; 95% CI, 0.32-0.39; $p < 0.0001$) were significantly less likely to have a second trimester obstetrical ultrasound.

Compared to individuals who resided in a neighbourhood in the lowest income quintile, those who resided in a neighbourhood in the highest income quintile were 86% more likely to have a second trimester obstetrical ultrasound exam (aOR, 1.86 highest vs. lowest income quintile; 95% CI, 1.62-2.13; $p < 0.0001$), though individuals in the second-lowest income quintile were 16% less likely to have a second trimester obstetrical ultrasound exam (aOR, 0.84; 95% CI,

0.76-0.93; $p < 0.0001$). It is acknowledged that data for neighbourhood income quintile were available only from January 2014 to October 2017, resulting in a substantial proportion of missing data.

Women with an Obstetric Comorbidity Index value of 3 or 4 were more likely to have a second trimester ultrasound exam (aOR, 1.15 vs. Obstetric Comorbidity Index of 0; 95% CI, 1.07-1.24; $p < 0.0001$) and women with an Obstetric Comorbidity Index value of ≥ 5 were less likely to have a second trimester ultrasound exam (aOR, 0.90 vs. Obstetric Comorbidity Index of 0; 95% CI, 0.83-0.98; $p < 0.0001$), though adjusted odds ratios at other levels were not statistically significant (Table 4.2).

Census divisions with individuals most likely to have a second trimester obstetrical ultrasound were generally those adjacent to large population centres (population of 100,000 or more, including Saskatoon and Regina) or medium population centres (population 30,000 to 99,999, including Prince Albert and Moose Jaw), as shown in Figure 4.2. Individuals residing in the northern part of the province where limited ultrasound facilities exist, as well as the western census divisions of the province, were less likely to have a second trimester ultrasound. Variation was seen among the medium and large population centres in Saskatchewan, despite each of these cities having readily available ultrasound facilities. Adjusted odds ratios of having a second trimester ultrasound were 0.77 (95% CI, 0.69-0.86), 0.83 (95% CI, 0.62-1.12), and 1.38 (95% CI, 0.96-1.99) for Regina, Prince Albert, and Moose Jaw, respectively, relative to Saskatoon.

4.4.3 Predictors of overall ultrasound imaging utilization during pregnancy

At least one obstetrical ultrasound exam was performed during 71,227 (88.4%) pregnancies. The average number (\pm standard deviation) of obstetrical ultrasound visits per pregnancy was 3.3 (± 3.0) across all pregnancies and 4.1 (± 3.1) in pregnancies carried to at least 23 weeks. This included first trimester ($n = 80,922$), second trimester ($n = 76,254$), and third trimester ($n = 49,390$) exams; biophysical profiles ($n = 29,420$); and fetal echocardiography ($n = 807$).

Advanced maternal age, higher Obstetrical Comorbidity Index, and higher neighbourhood income quintile were associated with a higher rate of obstetrical ultrasound exams based on univariate Poisson regression analysis (all $p < 0.0001$). First Nations status, higher gravidity, higher parity, rural residence, and higher index of remoteness were associated

Table 4.2. Comparison of individuals with and without a second trimester ultrasound exam performed

Variable	Pregnancies with a second trimester ultrasound exam performed (n = 50,180)	Pregnancies with no second trimester ultrasound exam performed (n = 7,006)	Adjusted odds ratio of a second trimester ultrasound exam performed (95% CI)*	p-value
Maternal age, years, mean (\pm SD)	27.7 \pm 5.4	26.0 \pm 5.9	1.03 (1.03-1.04) [†]	<0.0001
Status First Nations, n (%)				
No (reference)	40,865 (81%)	4,044 (58%)	—	<0.0001
Yes	9,315 (19%)	2,962 (42%)	0.50 (0.46-0.53)	
Gravidity, n (%)				
1 (reference)	25,583 (51%)	3,237 (46%)	—	<0.0001
2	11,783 (23%)	1,364 (19%)	1.19 (1.10-1.28)	
3	6,298 (13%)	898 (13%)	1.22 (1.08-1.37)	
≥ 4	6,516 (13%)	1,507 (22%)	1.25 (1.09-1.43)	
Parity, n (%)				
0 (reference)	39,112 (78%)	4,706 (67%)	—	<0.0001
1	6,416 (13%)	993 (14%)	0.77 (0.69-0.86)	
2	2,542 (5%)	618 (9%)	0.54 (0.46-0.63)	
≥ 3	2,110 (4%)	689 (10%)	0.44 (0.37-0.52)	
Obstetric Comorbidity Index, n (%)				
0 (reference)	28,433 (57%)	3,908 (56%)	—	<0.0001
1-2	3,791 (8%)	507 (7%)	0.92 (0.82-1.02)	
3-4	11,483 (23%)	1,521 (22%)	1.15 (1.07-1.24)	
≥ 5	6,473 (13%)	1,070 (15%)	0.90 (0.83-0.98)	
Location of residence, n (%)				
Urban (reference)	32,329 (64%)	3,146 (45%)	—	<0.0001
Rural	4,672 (9%)	820 (12%)	0.70 (0.63-0.77)	
Missing	13,179 (26%)	3,040 (43%)	0.51 (0.43-0.61)	

Index of remoteness, n (%)				
<0.23 (reference)	22,837 (46%)	1,533 (22%)	—	<0.0001
0.23-0.30	11,031 (22%)	2,043 (29%)	0.44 (0.41-0.48)	
0.31-0.40	9,995 (20%)	1,491 (21%)	0.54 (0.49-0.59)	
≥0.41	5,970 (12%)	1,901 (27%)	0.35 (0.32-0.39)	
Missing	347 (1%)	38 (1%)	1.04 (0.72-1.52)	
Neighbourhood income quintile, n (%)				
1 (reference)	8,461 (17%)	1,225 (17%)	—	<0.0001
2	6,793 (14%)	1,025 (15%)	0.84 (0.76-0.93)	
3	6,491 (13%)	688 (10%)	1.15 (1.03-1.29)	
4	7,350 (15%)	587 (8%)	1.50 (1.34-1.69)	
5	5,278 (11%)	336 (5%)	1.86 (1.62-2.13)	
Missing	15,807 (32%)	3,145 (45%)	1.79 (1.50-2.13)	

* Adjusted for all other variables in the multivariate generalized estimating equation model.

† Odds ratio for each 1-year increase in age.

SD, standard deviation.

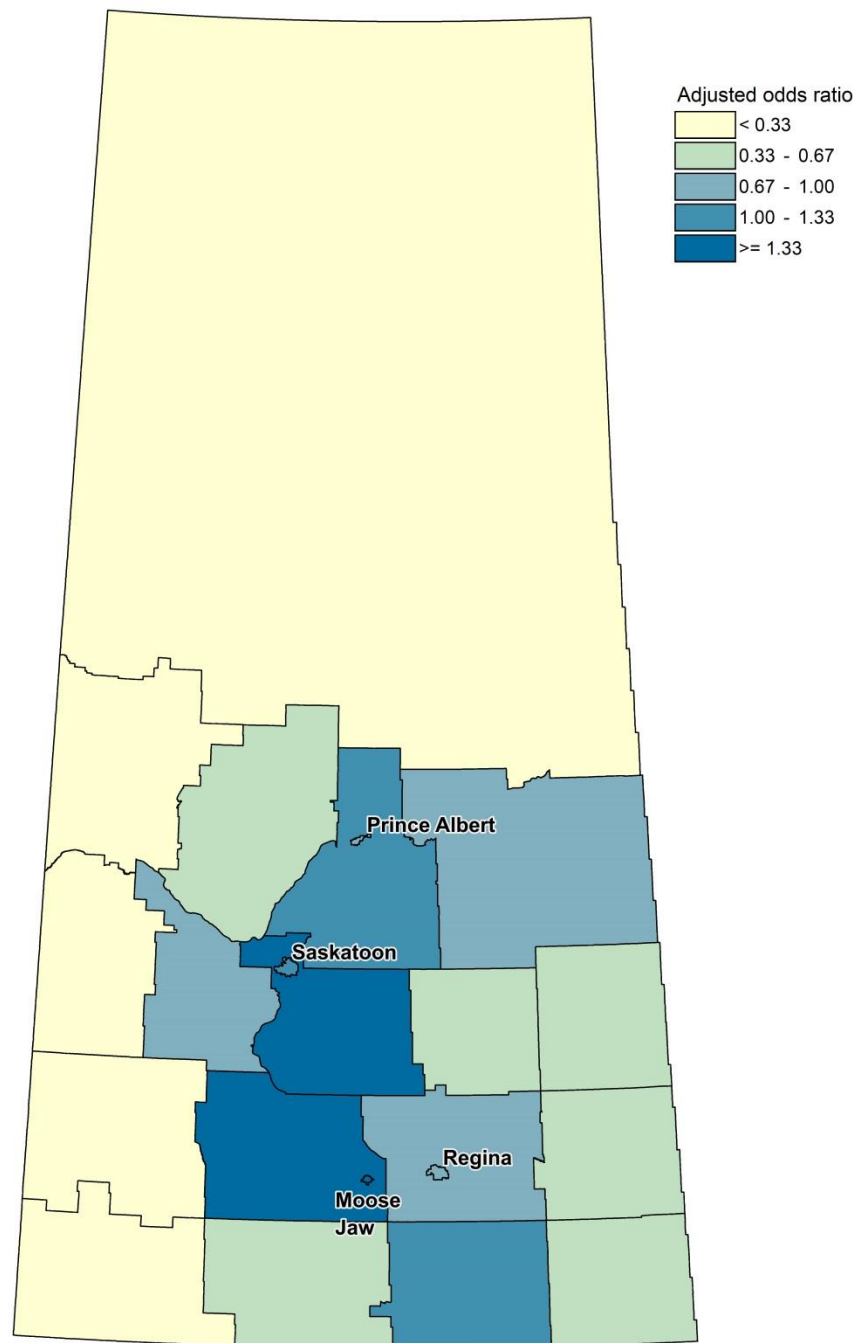


Figure 4.2. Choropleth map indicating adjusted odds ratios of having a second trimester obstetrical ultrasound exam for each census division in Saskatchewan. Boundaries of all 18 census divisions in the province are outlined in black. In addition, all large and medium population centres (Saskatoon, Regina, Prince Albert, and Moose Jaw) are labeled. The reference category is Saskatoon, the largest population centre in the province.

with a lower rate of obstetrical ultrasound exams based on univariate Poisson regression analysis (all $p < 0.0001$).

Following multivariate GEE Poisson regression analysis, advanced maternal age (aIRR, 1.33 for women ≥ 33 years old vs. < 23 years old; 95% CI 1.31-1.36; $p < 0.0001$), higher Obstetric Comorbidity Index (aIRR, 2.13 for Obstetric Comorbidity Index ≥ 5 vs. 0; 95% CI, 2.09-2.17; $p < 0.0001$), and higher neighbourhood income (aIRR, 1.10 for highest vs. lowest quintile; 95% CI, 1.07-1.12; $p < 0.0001$) were significantly associated with a higher rate of obstetrical ultrasound exams (Table 4.3).

First Nations status (aIRR, 0.80; 95% CI, 0.78-0.81; $p < 0.0001$), higher parity (aIRR, 0.73 for parity ≥ 3 vs. 1; 95% CI, 0.71-0.76; $p < 0.0001$), and higher index of remoteness (aIRR, 0.79 for index of remoteness ≥ 0.41 vs. < 0.23 ; 95% CI, 0.77-0.81; $p < 0.0001$) were significantly associated with lower rates of obstetrical ultrasound exams. Rural residence was not statistically significant in the multivariate GEE model and no clear trend was observed with increasing gravidity.

While northern and western census divisions were found to have lower aIRRs compared to census divisions in the central aspect of the province (similar to that seen for second trimester complete obstetrical ultrasound utilization), census divisions in the southeast had the highest rates of overall obstetrical ultrasound utilization (Figure 4.3). Adjusted incidence rate ratios for overall obstetrical ultrasound utilization were 1.19 (95% CI, 1.17-1.21), 0.94 (95% CI, 0.90-0.98), and 1.13 (95% CI, 1.08-1.18) for Regina, Prince Albert, and Moose Jaw, respectively, relative to Saskatoon.

4.5 Discussion

This study identifies marked disparities in obstetrical ultrasound utilization, including utilization of second trimester obstetrical ultrasound, among specific demographic groups. Individuals residing in lower income neighbourhoods, status First Nations individuals, and those residing in rural and remote areas, among other factors, were less likely to have a second trimester ultrasound exam and/or had lower rates of obstetrical ultrasound imaging utilization in general.

Findings from this study can be understood in the context of theoretical frameworks of health services utilization. A dominant theoretical framework to understand health services

Table 4.3. Number of pregnancies, number of obstetrical ultrasound exams, and rates of obstetrical ultrasound exams per pregnancy by sociodemographic and geographic factors

Variable	Number of pregnancies	Total number of obstetrical ultrasound exams	Average number of ultrasound exams per pregnancy	Adjusted IRR for obstetrical ultrasound exams per pregnancy (95% CI)*	p-value
Maternal age, years, n (%)					
<23 (reference)	18,157 (23%)	46,565 (18%)	2.56	—	<0.0001
23-26	13,171 (16%)	41,137 (16%)	3.12	1.19 (1.16-1.21)	
27-29	16,440 (20%)	56,103 (21%)	3.41	1.25 (1.23-1.28)	
30-32	14,616 (18%)	53,139 (20%)	3.64	1.30 (1.28-1.33)	
≥33	18,152 (23%)	67,515 (26%)	3.72	1.33 (1.31-1.36)	
Status First Nations, n (%)					
No (reference)	63,158 (78%)	221,066 (84%)	3.50	—	<0.0001
Yes	17,378 (22%)	43,393 (16%)	2.50	0.80 (0.78-0.81)	
Gravidity, n (%)					
1 (reference)	29,609 (37%)	98,864 (37%)	3.34	—	<0.0001
2	21,380 (27%)	73,173 (28%)	3.42	0.98 (0.97-0.99)	
3	12,855 (16%)	42,896 (16%)	3.34	1.02 (1.00-1.04)	
≥4	16,692 (21%)	49,526 (19%)	2.97	1.01 (0.98-1.03)	
Parity, n (%)					
0 (reference)	57,099 (71%)	196,457 (74%)	3.44	—	<0.0001
1	12,671 (16%)	39,073 (15%)	3.08	0.87 (0.86-0.89)	
2	5,683 (7%)	16,108 (6%)	2.83	0.82 (0.80-0.85)	
≥3	5,083 (6%)	12,821 (5%)	2.52	0.73 (0.71-0.76)	
Obstetric Comorbidity Index, n (%)					
0 (reference)	50,099 (62%)	128,489 (49%)	2.56	—	<0.0001
1-2	5,847 (7%)	22,797 (9%)	3.90	1.48 (1.45-1.51)	
3-4	15,389 (19%)	63,705 (24%)	4.14	1.65 (1.63-1.67)	
≥5	9,201 (11%)	49,468 (19%)	5.38	2.13 (2.09-2.17)	

Location of residence, n (%)					
Urban (reference)	50,747 (63%)	175,477 (66%)	3.46	–	<0.0001
Rural	7,597 (9%)	25,006 (9%)	3.29	1.01 (0.99-1.04)	
Missing	22,192 (28%)	63,976 (24%)	2.88	0.93 (0.90-0.96)	
Index of remoteness, n (%)					
<0.23 (reference)	35,794 (44%)	130,177 (49%)	3.64	–	<0.0001
0.23-0.30	18,168 (23%)	54,657 (21%)	3.01	0.86 (0.85-0.88)	
0.31-0.40	15,675 (19%)	51,336 (19%)	3.28	0.94 (0.93-0.96)	
≥0.41	10,395 (13%)	26,760 (10%)	2.57	0.79 (0.77-0.81)	
Missing	504 (1%)	1,529 (1%)	3.03	0.93 (0.85-1.00)	
Neighbourhood income quintile, n (%)					
1 (reference)	13,865 (17%)	43,957 (17%)	3.17	–	<0.0001
2	11,214 (14%)	35,993 (14%)	3.21	0.97 (0.95-0.99)	
3	10,226 (13%)	35,151 (13%)	3.44	1.01 (0.99-1.04)	
4	11,174 (14%)	40,094 (15%)	3.59	1.04 (1.02-1.06)	
5	7,993 (10%)	29,929 (11%)	3.74	1.10 (1.07-1.12)	
Missing	26,064 (32%)	79,335 (30%)	3.04	1.07 (1.04-1.10)	

* Adjusted for all other variables in the multivariate generalized estimating equation model.

CI, confidence interval; IRR, incidence rate ratio.

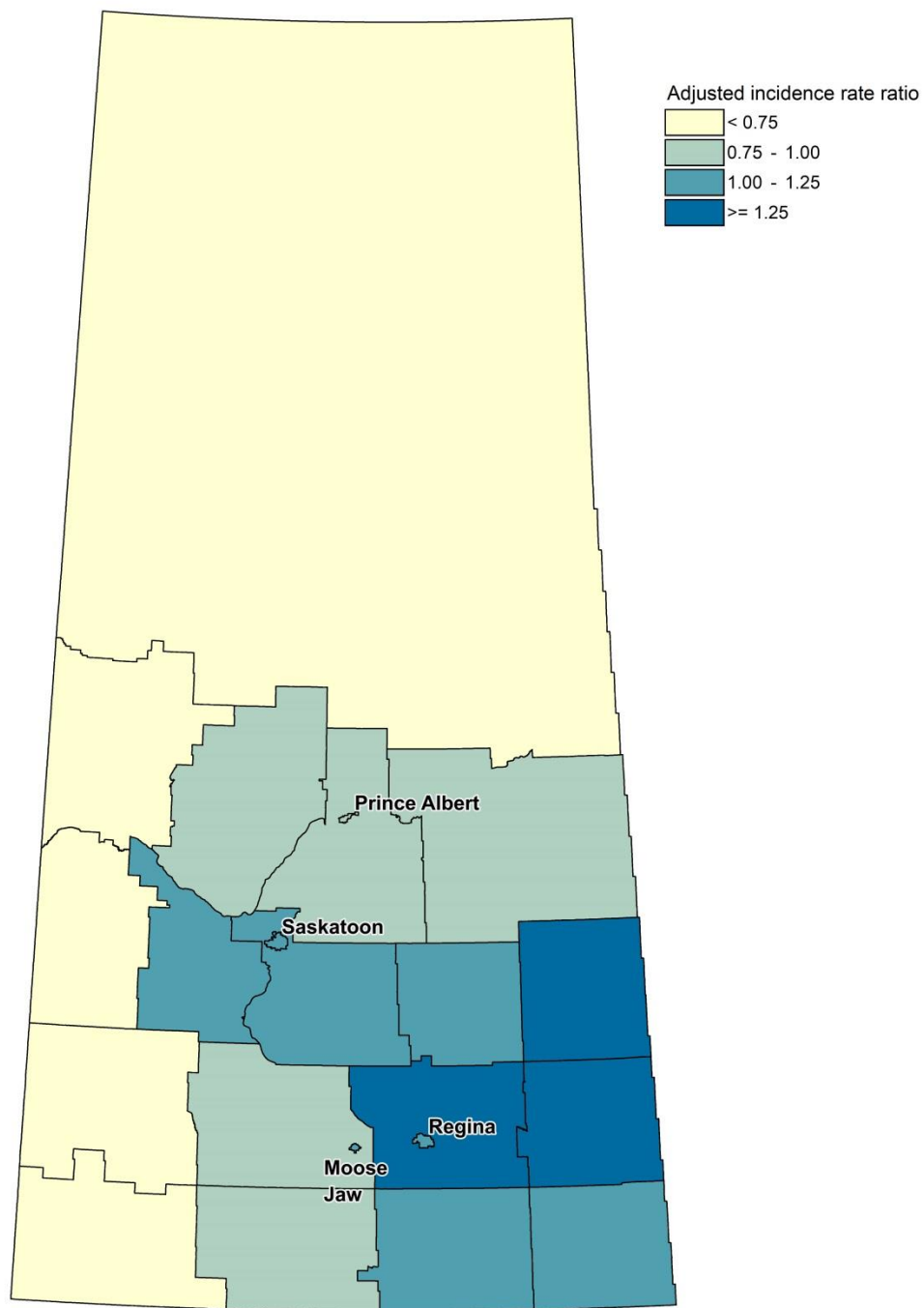


Figure 4.3. Choropleth map indicating adjusted incidence rate ratios of overall obstetrical ultrasound imaging for each census division in Saskatchewan. Boundaries of all 18 census divisions in the province are outlined in black. In addition, all large and medium population centres (Saskatoon, Regina, Prince Albert, and Moose Jaw) are labeled. The reference category is Saskatoon, the largest population centre in the province.

utilization is Andersen's Behavioral Model of Health Services Use.^{172,179} Initially described in the late 1960s,¹⁷⁹ this model posits that use of health services is a function of individuals' predisposition to use services ("predisposing characteristics"), factors which enable or impede use ("enabling resources"), and individuals' perceived and evaluated need for care.¹⁷² Predisposing characteristics include demographic characteristics, including age and sex; social structure, including education, occupation, and ethnicity; and health beliefs. Enabling resources according to the Behavioral Model include health personnel, facilities, a referral for obstetrical ultrasound, as well as the means for individuals to avail themselves of ultrasound services, including income, means of travel, and reasonable wait times.¹⁷² Andersen's concept of "enabling resources" reflects dimensions of accessibility as described by Levesque et al. in his framework of access to care, including approachability, acceptability, availability and accommodation, affordability, and appropriateness.⁴⁸ In our study, consistent with Andersen's theoretical model, predisposing characteristics (including maternal age) and women's need for ultrasound (comorbidities and risk factors as reflected in the Obstetric Comorbidity Index) were independently associated with increased levels of obstetrical ultrasound imaging utilization.

Other factors need to be unpacked further in the context of this model and other literature. Our study found that Indigenous peoples were less likely to have a second trimester obstetrical ultrasound exam and had a lower rate of obstetrical ultrasound exams overall, consistent with prior literature which has found Indigenous peoples to have lower rates of prenatal care in general.^{175–177} Prior research has also demonstrated lower utilization of screening mammography programs among Indigenous peoples,¹⁹¹ including when those services are provided using a mobile mammography unit as has recently been described on Native American reservations in the United States.¹⁹² Our previous qualitative study exploring access to ultrasound in northern, remote, Indigenous communities found that Indigenous peoples highly value obstetrical ultrasound to provide reassurance about fetal development, and, in some cases, considered diagnostic information provided by ultrasound imaging to be "lifesaving."¹⁷¹ Considering these findings, decreased utilization of obstetrical ultrasound among Indigenous peoples cannot be attributed solely to personal or cultural values among Indigenous peoples. Rather, other systemic barriers (represented by predisposing characteristics as part of the "social structure" in Anderson's model) must be explored and addressed. It is recognized in the literature that Indigenous peoples face racism and discrimination when accessing care and as a result

Indigenous peoples may be reluctant to access healthcare services.¹⁸ Providing culturally-safe imaging care through increased cultural safety training among healthcare providers and collaborating with Indigenous patients and Elders to co-design culturally safe programs to enhance equitable access to obstetrical ultrasound and ensure culturally safe imaging experiences are potential approaches to help ensure Indigenous peoples have equitable opportunity to receive obstetrical ultrasound. Ensuring optimal access to obstetrical ultrasound among Indigenous peoples may be particularly important, as Indigenous peoples have a higher rate of stillbirths compared to non-Indigenous peoples^{20,21} and two-fold higher maternal mortality rate relative to the general Canadian population.¹⁹³

Our study also demonstrated that patients living in rural and remote communities were less likely to have a second trimester ultrasound exam. This is in contrast to some previous research in Canada which has presented mixed results regarding whether urban-rural status is associated with inadequate prenatal care utilization.^{173,176,177} These differences might be explained by the outcome measured. For example, a study which did not find urban-rural status to be significantly associated with inadequate prenatal care used the Adequacy of Prenatal Care Utilization Index to assess adequacy of prenatal care.¹⁷³ This index considers only the timing of initiation of prenatal care and the frequency of prenatal visits, and does not consider obstetrical ultrasound, which requires specialized personnel and equipment that is not as readily available in many communities.¹⁹⁴ Applying Andersen's Behavioural Model,¹⁷² lower rates of obstetrical ultrasound in rural and remote communities may relate to disparities in "enabling resources," including a referral for an obstetrical ultrasound, increased remoteness from ultrasound facilities, limited means to travel to an ultrasound facility, and lengthy wait times for an ultrasound appointment in remote communities. Indeed, the barriers identified in our group's previous research on access to ultrasound imaging¹⁷¹ appear to be reflected as decreased ultrasound imaging utilization in the present study.

The use of innovative technologies such as telerobotic ultrasound should be explored to improve access to ultrasound services for rural and remote populations.^{54,167} Telerobotic ultrasound allows sonographers, radiologists, or obstetricians to remotely scan patients from a central location while patients stay in their home community for their obstetrical ultrasound exam.^{5,54,167} Our experience using telerobotic ultrasound in northern Saskatchewan during the COVID-19 pandemic indicates clinical effectiveness and a high degree of patient acceptance of

this technology, suggesting that this may be a viable means of improving access to ultrasound services in rural and remote communities.¹⁶⁸ Ensuring culturally safe implementation of imaging services is critical to ensure acceptability and approachability.¹⁹⁵

Consistent with prior literature investigating inadequate prenatal care in general,^{174,176,177,196} in our study there was a trend of patients with higher socioeconomic status being more likely to have a second trimester ultrasound exam, with higher rates of obstetrical ultrasound overall. This is in contrast to a study which found increased rates of obstetrical ultrasound imaging among patients of lower socioeconomic status in an urban setting in Manitoba, Canada. This difference may be explained by our study controlling for covariates such as First Nations status, multiparity, and obstetrical risk factors, which the previous study did not control for.¹⁸⁷ Interestingly, individuals in the second-lowest income quintile in our study had lower rates of obstetrical ultrasound and lower odds of having a second trimester ultrasound exam compared to the lowest income quintile. It is plausible that patients in the lowest income quintile are recognized as being most at-risk for inadequate prenatal care and thus are followed more closely by their primary healthcare provider and provided with additional supports to ensure they are able to access investigations such as obstetrical ultrasound.

While two obstetrical ultrasound exams are recommended in an uncomplicated pregnancy (first trimester ultrasound and second trimester ultrasound), there are multiple clinical indications in which additional obstetrical ultrasound exams are recommended.^{135,197} The number of clinically-indicated ultrasound exams during a pregnancy is individual- and pregnancy-specific, and for this reason the appropriate number of exams for this cohort is not known. The average number of obstetrical ultrasound visits reported in our study is within the range previously reported in the literature, which has ranged from 2.14 ultrasound exams per pregnancy (in a randomized controlled trial in Finland)¹⁹⁸ to 4.55 ultrasound exams per pregnancy (based on United States data provided by insurance providers and underwriters for singleton, low-risk deliveries, with the potential for multiple exam codes to be billed at each ultrasound visit)¹⁹⁹. Differences in utilization between sociodemographic groups even after controlling for variables which may result in an increased number of obstetrical ultrasound exams—such as maternal age and Obstetric Comorbidity Index—suggest unequal utilization potentially stemming from inequitable access. This is of particular concern considering that some sociodemographic groups identified in this study—including Indigenous patients and low income

patients—have increased rates of adverse pregnancy outcomes.^{20,21,193} While overutilization of obstetrical ultrasound imaging is not specifically accounted for in this study, the fact that the same sociodemographic and geographic predictors of having a second trimester complete ultrasound (which is recommended for all pregnant women) were also significant predictors of overall obstetrical ultrasound utilization suggests that disparities in utilization are not simply due to overutilization among some sociodemographic groups. Future work should include subgroup analyses, including among First Nations people and non-First Nations people, to better understand factors associated with obstetrical ultrasound utilization among each subgroup. Future work should also investigate differences in maternal and fetal outcomes as a result of variation in obstetrical ultrasound utilization.

Despite each of the medium and large population centres in the province having readily available access to ultrasound facilities, substantial variability was observed for second trimester obstetrical ultrasound utilization and overall obstetrical ultrasound utilization after controlling for covariates such as maternal age, First Nations status, neighbourhood income, and Obstetric Comorbidity Index. This may reflect differences in regional physician ordering practices or the type of obstetrical care provider. One study based on survey data found that obstetricians were more likely to order obstetrical ultrasound exams for a given patient compared to family physicians, midwives and nurse practitioners.²⁰⁰ While this may be due to the complexity of patients who are managed by obstetricians compared to family physicians, midwives and nurse practitioners, variation by type of obstetrical care provider deserves further attention. Lack of obtaining a second trimester ultrasound may be secondary to patient barriers in accessing ultrasound facilities, patients not being connected with an obstetrical care provider by the gestational age the exam is usually performed, or the obstetrical care provider simply not offering patients a second trimester ultrasound.

There are some limitations to this study, including those related to the use of administrative data as the basis for the study. Administrative data may have coding errors and incomplete data, potentially introducing systematic biases.¹⁷⁶ In our study, data for urban vs. rural status and neighbourhood income quintile were available only from January 2014 to October 2017, resulting in a substantial proportion of missing data for these variables. As posited by various theoretical models of healthcare utilization, additional variables may help explain obstetrical ultrasound utilization, such as education level, occupation, and culture, but are not

reliably captured in available administrative datasets. There is a trade-off between being able to obtain detailed individual level data (as might be achieved through conducting a chart review or prospective survey) and being able to capture the entire population in the study cohort. This study favoured the latter, though a future, complementary study might investigate the association between obstetrical imaging utilization and additional variables using a different study design.

Another limitation due to lack of data availability is the use of neighbourhood (area-level) income quintile rather than individual income as a co-variate to represent socioeconomic status. While studies have found that there can be substantial variability between household-level income and area-level income,^{201,202} area-level income remains recognized as an independently meaningful predictor and remains commonly used as a proxy of socioeconomic status.^{202,203} Additionally, from a social-ecologic perspective, area-level measures of socioeconomic status are considered meaningful indicators in and of themselves and should not be simply considered proxies for individual-level data.^{176,204} Another limitation is that location of residence (including urban vs. rural status and index of remoteness) was determined only at the start of each pregnancy. Individuals may have moved during their pregnancy, though the proportion of patients who moved is considered minimal. Further, although the Obstetrical Comorbidity Index was used as a proxy to reflect certain clinical conditions, such as multiple gestation, which may predispose individuals to an increased number of obstetrical ultrasound exams, the comorbidities on which it is based is not all-encompassing.

4.6 Conclusion

This study identifies specific sociodemographic groups who were less likely to have a second trimester ultrasound exam and had lower rates of obstetrical ultrasound imaging utilization in general. Disparities in utilization may reflect structural barriers to accessing obstetrical ultrasound which are faced by specific sociodemographic groups, including rural and remote, Indigenous, and low-income individuals. This study may inform the development of programs and services targeted towards sociodemographic groups and geographic regions which currently have lower rates of obstetrical ultrasound utilization to ensure that all women have equitable opportunity for obstetrical ultrasound imaging. It is our hope that this study stimulates further work exploring solutions to overcome these systemic barriers, including the use of

innovative technologies to improve access to diagnostic ultrasound services for vulnerable and marginalized populations.

4.7 Acknowledgements

We would like to thank Sonia Vanderby, Saskatchewan Health Quality Council, for her assistance in facilitating use of province-wide databases, and Rob Anderson, eHealth Saskatchewan, for assistance in creating the choropleth maps. This work was supported by the Saskatchewan Health Research Foundation and Saskatchewan Centre for Patient-Oriented Research.

4.8 Disclosure

This study is based on de-identified data provided by the Saskatchewan Ministry of Health and eHealth Saskatchewan. The interpretation and conclusions contained herein do not necessarily represent those of the Government of Saskatchewan, the Saskatchewan Ministry of Health, or eHealth Saskatchewan.

CHAPTER 5

SOCIODEMOGRAPHIC AND GEOGRAPHIC FACTORS ASSOCIATED WITH NON-OBSTETRICAL ULTRASOUND IMAGING UTILIZATION: A POPULATION-BASED STUDY*

Chapter 4 provided evidence suggesting that the structural barriers which individuals living in rural and remote communities, Indigenous persons, and individuals living in low income neighbourhoods face in accessing ultrasound imaging result in lower rates of obstetrical ultrasound utilization. Based on this study, it was hypothesized that structural barriers to accessing ultrasound services among these sociodemographic and geographic groups would also result in decreased rates of *non-obstetrical* ultrasound. As such, Chapter 5 presents a population-based study to assess the relationship between sociodemographic and geographic factors and non-obstetrical ultrasound utilization. The study's results demonstrate substantial variation in non-obstetrical ultrasound utilization among individuals residing at variable levels of remoteness from urban centres, possibly reflecting barriers patients face in accessing medical imaging modalities, including ultrasound imaging.

* This chapter is based on:
Adams SJ, Yao S, Mondal P, Lim H, Mendez I, Babyn P. Sociodemographic and geographic factors associated with non-obstetrical ultrasound imaging utilization: a population-based study. *Can Assoc Radiol J* (accepted)

5.1 Abstract

Objective: Ultrasound is one of the most commonly used imaging modalities, though some populations face barriers in accessing ultrasound services, potentially resulting in disparities in utilization. The objective of this study was to assess the association between sociodemographic and geographic factors and non-obstetrical ultrasound utilization in the province of Saskatchewan, Canada.

Methods: All non-obstetrical ultrasound exams performed from 2014-2018 in Saskatchewan, Canada were retrospectively identified from province-wide databases. Univariate and multivariate Poisson regression analyses were performed to assess the association between ultrasound utilization and sex, age, First Nations status, Charlson Comorbidity Index, urban vs. rural residence, geographic remoteness, and neighbourhood income.

Results: A total of 1,324,846 individuals (5,857,044 person-years) were included in the analysis. Female sex (adjusted incidence rate ratio [aIRR], 2.20; 95% confidence interval [CI], 2.19-2.22), age (aIRR, 4.97; 95% CI, 4.90-5.05 for ≥ 57 years vs. < 11 years), comorbidities (aIRR, 4.36 for Charlson Comorbidity Index > 10 vs. 0; 95% CI, 3.78-5.03), and higher neighbourhood income (aIRR, 1.04; 95% CI, 1.02-1.05 for highest vs. lowest quintile) were associated with higher rates of ultrasound utilization. Individuals who were status First Nations (aIRR, 0.91; 95% CI, 0.90-0.92) or resided in geographically remote areas (aIRR, 0.87 for most vs. least remote; 95% CI, 0.83-0.91) had lower rates of ultrasound utilization. Individuals who lived in a rural area also had lower rates of ultrasound utilization (aIRR, 0.93; 95% CI, 0.92-0.94).

Conclusion: Substantial disparities exist in non-obstetrical ultrasound utilization among individuals in low-income neighbourhoods, status First Nations individuals, and individuals in rural and remote communities.

5.2 Introduction

Ultrasound imaging is one of the most commonly used medical imaging modalities.¹³³ Despite its importance in clinical care, ultrasound is not available in many rural and remote communities in Canada and around the world, creating inequities in access to this important imaging modality.¹⁷¹

While disparities in *access* to ultrasound imaging among specific sociodemographic groups—including individuals in rural and remote communities—have been reported,¹⁷¹ it is less clear how disparities in access to ultrasound imaging impact *utilization* of non-obstetrical ultrasound imaging. One of the most frequently cited theoretical models of healthcare utilization, first described by Andersen in 1968, proposes that healthcare utilization can be predicted by an individuals' predisposition to use services, factors which enable or impede use, and individuals' perceived and evaluated need for care.^{172,179} Factors which enable or impede use reflect many dimensions of accessibility to healthcare services, described by Levesque et al. as approachability, acceptability, availability and accommodation, affordability, and appropriateness.⁴⁸

A number of sociodemographic factors, such as age, race, income, and education level, have been found to be predictors of healthcare utilization in general.^{173–177,205–207} Less research has focused on sociodemographic and geographic predictors of imaging utilization, including utilization of ultrasound. Our previous research found that status First Nations individuals, individuals residing in rural and remote areas, and individuals in low-income neighbourhoods were less likely to have a second trimester obstetrical ultrasound.²⁰⁸ However, it is unclear whether these factors are also associated with non-obstetrical ultrasound, which is commonly used as a diagnostic tool for specific clinical symptoms, in contrast to second trimester obstetrical ultrasound which is recommended for all pregnant patients.¹³⁶

Multiple studies have demonstrated benefits of medical imaging such as reduced rates of unnecessary surgeries and reduced length of hospital stays, underscoring the importance of equitable access to and utilization of imaging.^{209,210} Additionally, lack of imaging could result in delays in diagnosis and treatment, potentially leading to increased utilization of other healthcare services.¹³² As such, it is critical to consider disparities in imaging utilization which may reflect barriers patients face in accessing imaging services. Thus, the objective of this study was to assess the association between sociodemographic and geographic factors and non-obstetrical diagnostic ultrasound utilization.

5.3 Methods

This study was determined to be exempt from research ethics approval by the University of Saskatchewan Research Ethics Board. Access to data used in this study was facilitated through

a data sharing agreement between the Saskatchewan Health Quality Council, eHealth Saskatchewan, Saskatchewan Health Authority, Ministry of Health, and University of Saskatchewan.

5.3.1 Study cohort

All individuals registered for medical services in Saskatchewan, Canada between January 1, 2014 and December 31, 2018 (the “study period”) were eligible for inclusion. Individuals who were registered for medical services in Saskatchewan for less than 180 days during the study period (as a result of birth, death, or relocation to or from Saskatchewan) were excluded. Individuals were identified from the Saskatchewan Personal Health Registration System and individual-level records were linked across province-wide administrative health databases (Table 5.1).

5.3.2 Explanatory and outcome variables

5.3.2.1 Explanatory variables

Demographic information, including age, sex, and First Nations status, was abstracted from the Personal Health Registration System for each individual in the study cohort. Age was defined as of January 1, 2014 or, if not registered for health services as of January 1, 2014, the date on which the individual became registered for health services. First Nations status was indicated if a First Nations individual self-identified as a status Indian as defined by the *Indian Act*.

The Charlson Comorbidity Index (CCI) was used a proxy for health status.²¹¹ This index was initially developed to predict risk of death within 1 year of hospitalization based on diagnosis codes for 17 diseases and has been validated to predict individuals who will incur high healthcare costs.^{212–214} The CCI was determined for each individual based on ICD-10-CA diagnosis codes from the Discharge Abstract Database and ICD-9 diagnosis codes from the Medical Services Branch (MSB) physician billing database.²¹²

Location of residence (urban vs. rural) was determined based on each individual’s physical residence listed in the Personal Health Registration System. Urban was defined to include all population centres (communities with a population of at least 1,000 and a population density of 400 persons or more per square kilometre) and rural was defined as all territory excluding population centres.¹⁸⁶ Based on limitations in the Saskatchewan Health Quality Council’s administrative dataset as a result of a change in licensing of the Postal Code

Table 5.1. Description of databases

Database	Description of database	Variables abstracted from database	Time period of data availability
Personal Health Registration System	Includes all individuals registered for provincial medical services in Saskatchewan. This includes approximately 99% of the population of Saskatchewan, and excludes federal penitentiary inmates, Royal Canadian Mounted Police, and veterans. ²¹²	Age	Jan 2014 – Dec 2018
		Sex	Jan 2014 – Dec 2018
		First Nations status	Jan 2014 – Dec 2018
		Location of residence (rural vs. urban)*	Jan 2014 – Oct 2017
		Index of remoteness*	Jan 2014 – Dec 2018
		Neighbourhood income quintile*	Jan 2014 – Oct 2017
Discharge Abstract Database	Includes administrative, clinical, and demographic information regarding hospital discharges, including deaths, transfers, and sign-outs, across all hospitals in Saskatchewan. Diagnoses, conditions, and problems related to each patient's hospital stay are coded based on the International Statistical Classification of Diseases and Related Health Problems, 10th revision, Canada (ICD-10-CA). ²¹⁵	Charlson Comorbidity Index†	Jan 2014 – Dec 2018
Ministry of Health MSB physician billing database	Includes billing claims from physicians remunerated on a fee-for-service basis, as well as shadow billing claims for non-fee-for-service physicians. For ultrasound imaging, MSB billing data capture ultrasound exams billed in private facilities in Saskatchewan based on fee codes as listed in the provincial <i>Payment Schedule for Insured Services Provided by a Physician</i> . ²¹⁶ In addition to fee codes, a three-digit diagnosis code based on the International Classification of Diseases, Ninth Revision (ICD-9) is recorded with each billing claim.	Charlson Comorbidity Index†	Jan 2014 – Dec 2018
		Number and type of ultrasound exams	Jan 2014 – Dec 2018
Provincial RIS	Includes all ultrasound exams performed in public facilities in Saskatchewan	Number and type of ultrasound exams	Jan 2014 – Dec 2018

* Based on each individual's address and postal code

† Determined based on ICD-10-CA diagnosis codes from the Discharge Abstract Database and ICD-9 diagnosis codes from the MSB physician billing database²¹²

MSB, Medical Services Branch; RIS, Radiology Information System.

Conversion File, these data were only available from January 2014 to October 2017. For the period from October 2017 to December 2018, location of residence was based on each individual's residence as of October 2017.

An index of remoteness as a proxy for geographic remoteness was determined based on the census subdivision (CSD) of each individual's physical address listed in the Personal Health Registration System as maintained by eHealth Saskatchewan. This index of remoteness was developed by Statistics Canada to reflect proximity to general services such as health services, businesses, and education. Initial values for the index of remoteness were rescaled to the range of 0 (least remote) to 1 (most remote) based on Canada-wide data.¹⁸⁴ In contrast to other measures of proximity such as travel distance, this index minimizes biases for remote communities in which the dominant transportation method is air transportation. In statistical analyses, <0.23 was chosen as the reference category as the two largest cities in the province both had index of remoteness values slightly less than 0.23.

Socioeconomic status was represented in analyses by neighbourhood income quintile. As previously described, quintiles for each dissemination area were defined based on average income per single person equivalent from 2011 Census data.¹⁹⁰ The income quintile of the dissemination area in which each individual resided was assigned to that individual. As for urban vs. rural residence, data were only available from January 2014 to October 2017. For the period from October 2017 to December 2018, neighbourhood income quintile was based on each individual's residence as of October 2017.

All geographically based variables, including location of residence (urban vs. rural), index of remoteness, and neighbourhood income quintile, were specific to a time period defined by start and end dates, taking into account that individuals may move within the study period. For example, two separate time periods were defined if an individual moved from address A to address B, with each time period having different values for all geographically based variables.

5.3.2.2 Outcome variable

The primary outcome variable was the number of non-obstetrical ultrasound exams performed per person-year. Ultrasound exams were identified from the provincial Radiology Information System (RIS), which includes all exams performed in public facilities, and MSB physician billing database, which includes all exams performed in private facilities. Together,

these two databases include all publicly-funded diagnostic ultrasound exams billed in Saskatchewan.

Ultrasound exams performed on the same day which covered different anatomic regions (e.g. abdomen and pelvis) were counted as two separate exams. Exams which covered the same anatomic region but which were coded as two separate exams despite being part of the standard protocol of one of the exams performed at the same time (e.g. abdomen and renal) were counted as a single exam. Ophthalmic, cranial, joint (musculoskeletal), and breast ultrasound exams, echocardiography, and ultrasound-guided procedures were excluded from the study as these are specialized ultrasound exams not performed at all ultrasound centres. Obstetrical ultrasound exams were also excluded from this study and have been reported separately.²⁰⁸

5.3.3 Statistical analysis

Frequencies of each ultrasound exam type performed over the 5-year period and frequencies and proportions of the number of ultrasound exams performed per person-year were determined.

Univariate Poisson regression modeling was used to estimate incidence rate ratios (IRRs) and 95% confidence intervals (CIs) for each stratum of each predictor variable. Variables with $p < 0.20$ based on univariate analyses were included in a multivariate model with a Poisson distribution to identify factors associated with non-obstetrical ultrasound utilization. The logarithm of follow-up time within the 5-year study period was used as an offset variable. Missing values were considered as a special “missing” category in analyses, and no records were excluded due to missing data. Adjusted incidence rate ratios (aIRRs) and 95% CIs were determined for each stratum of each variable.

Correlation coefficients and variance inflation factors to assess for multicollinearity were determined. As correlation of 0.43 was found between location of residence (urban vs. rural) and index of remoteness, two multivariate models were fitted: a multivariate model with all variables except urban vs. rural location of residence (Model 1) and a multivariate model with all variables except index of remoteness (Model 2).

Adjusted incidence rate ratios were estimated for each census division and medium and large population centre in Saskatchewan and were plotted on a choropleth map to visualize geographic differences in rates of non-obstetrical ultrasound utilization. Choropleth maps were created using MapInfo Pro 2019 (Precisely, Pearl River, New York).

Statistical analyses were performed using SAS, version 9.4 (SAS Institute, Cary, NC). P-values less than 0.05 were considered statistically significant.

5.4 Results

A total of 1,358,113 individuals were identified in the Personal Health Registration System over the study period. Of these individuals, 33,267 individuals were registered for medical services for less than 180 days and were excluded. The remaining 1,324,846 individuals were registered for medical services for a total of 5,857,044 person-years over the 5-year study period and were included in the study.

The most common exams performed over the study period were pelvic, abdominal, superficial soft tissues, and renal ultrasound exams (Table 5.2). Seventy-one percent of individuals had no ultrasound exams over the 5-year study period, 14% had one, 7% had two, and 8% had three or more ultrasound exams (Table 5.3). 279,186 (34%) ultrasound exams were abstracted from RIS (representing exams performed in public facilities) and 548,624 (66%) exams were abstracted from the MSB physician billing database (representing exams performed in private clinics).

Table 5.2. Ultrasound exams by exam type over the 5-year study period

Type of exam	Total exams over study period	Ultrasound exams per 1000 person-years
Pelvis	233,566	39.88
Abdomen (complete)	217,937	37.21
Superficial soft tissues	102,484	17.50
Renal	96,047	16.40
Peripheral venous Doppler	48,332	8.25
Thyroid, parotid glands, or similar	43,639	7.45
Abdomen (limited)	26,138	4.46
Scrotum and testes	23,267	3.97
Carotid Doppler	13,849	2.36
Transvaginal ultrasound follicle tracking and intrauterine device localization	12,762	2.18
Other vascular Doppler (intraabdominal and pelvic)	8,737	1.49
Chest	6,884	1.18
Prostate	2,755	0.47
Other	682	0.12

Table 5.3. Number of ultrasound exams per individual over the 5-year study period

Number of ultrasound exams	n (%)
0	944,380 (71.3)
1	190,599 (14.4)
2	89,384 (6.7)
3	43,977 (3.3)
4	23,271 (1.8)
5	12,974 (1.0)
6	7,318 (0.6)
7	4,455 (0.3)
8	2,736 (0.2)
9	1,724 (0.1)
≥10	4,028 (0.3)

The overall rate of non-obstetrical ultrasound utilization was 0.141 ultrasound exams per person-year (0.102 ultrasound visits per person-year). Rates of ultrasound exams per person-year by sociodemographic and geographic factors are presented in Table 5.4.

Based on univariate Poisson regression analysis, female sex, higher age, higher CCI, and higher neighbourhood income were significantly associated with higher rates of ultrasound utilization. First Nations status, rural residence, and geographic remoteness were significantly associated with lower rates of ultrasound utilization (Table 5.5).

Based on multivariate Poisson regression analysis, female sex (Model 1—aIRR, 2.20; 95% CI, 2.19-2.22; $p<0.0001$; Model 2—aIRR, 2.21; 95% CI, 2.19-2.22; $p<0.0001$), higher age (Models 1 and 2—aIRR, 4.97 for age ≥ 57 years vs. <11 years; 95% CI, 4.90-5.05; $p<0.0001$), higher CCI (Model 1—aIRR, 4.36 for CCI >10 vs. 0; 95% CI, 3.78-5.03; $p<0.0001$; Model 2—aIRR, 4.39; 95% CI, 3.80-5.06; $p<0.0001$), and higher neighbourhood income (Model 1—aIRR, 1.04 for highest vs. lowest quintile; 95% CI, 1.02-1.05; $p<0.0001$; Model 2—aIRR, 1.03; 95% CI, 1.02-1.04; $p<0.0001$) were associated with higher rates of ultrasound utilization. Status First Nations individuals (Model 1—aIRR, 0.91; 95% CI, 0.90-0.92; $p<0.0001$; Model 2—aIRR, 0.90; 95% CI, 0.88-0.91; $p<0.0001$) and individuals living in a rural area (aIRR, 0.93; 95% CI, 0.92-0.94; $p<0.0001$) had lower rates of ultrasound utilization. Lower rates of ultrasound utilization were also observed for all levels of increased geographic remoteness relative to the reference

Table 5.4. Population characteristics and rate of ultrasound exams per person-year by sociodemographic and geographic factors

Variable	n	Total number of person-years	Total number of ultrasound exams	Ultrasound exams per person-year
Sex				
Male (reference)	669,076	2,944,447	269,835	0.0916
Female	655,770	2,912,596	557,975	0.1916
Age (years)				
<11 years (reference)	253,857	1,027,879	40,453	0.0394
11-25 years	258,944	1,157,597	114,168	0.0986
26-40 years	283,214	1,236,097	205,628	0.1664
41-56 years	256,927	1,198,574	204,331	0.1705
≥57 years	271,904	1,236,896	263,230	0.2128
First Nations status				
No (reference)	1,209,203	5,309,494	762,240	0.1436
Yes	115,643	547,549	65,570	0.1198
Charlson Comorbidity Index				
0 (reference)	1,035,934	4,510,221	534,006	0.1184
1-2	247,599	1,174,856	229,741	0.1955
3-4	27,440	117,976	40,430	0.3427
5-6	7,253	28,658	11,866	0.4141
7-8	4,141	16,393	7,578	0.4623
9-10	1,882	6,969	3,122	0.4480
>10	597	1,968	1,067	0.5422
Location of residence				
Urban (reference)	824,380	3,459,194	516,264	0.1492
Rural	140,942	542,736	74,126	0.1366
Missing	537,569	1,855,114	237,420	0.1280
Index of remoteness				
<0.23 (reference)	599,467	2,599,710	398,592	0.1533
0.23-0.30	282,610	1,265,389	178,529	0.1411
0.31-0.40	286,103	1,285,118	171,573	0.1335
0.41-0.50	110,625	497,791	56,777	0.1141
0.51-0.60	26,704	121,482	12,493	0.1028
>0.60	12,912	59,938	6,505	0.1085
Missing	6,425	27,614	3,341	0.1210
Neighborhood income quintile				
1 (reference)	237,525	774,102	113,817	0.1470
2	211,764	707,521	101,118	0.1429
3	205,883	720,780	106,827	0.1482
4	216,933	787,366	117,048	0.1487
5	191,484	731,504	108,420	0.1482
Missing	602,794	2,135,768	280,580	0.1314

Table 5.5. Results of univariate and multivariate Poisson regression analyses by sociodemographic and geographic factors

Variable	Unadjusted IRR (95% CI)	p- value*	Adjusted IRR – Model 1 (95% CI)†	Adjusted IRR – Model 2 (95% CI) ‡	p- value§
Sex		<0.0001			<0.0001
Male (reference)	–		–	–	
Female	2.11 (2.10-2.13)		2.20 (2.19-2.22)	2.21 (2.19-2.22)	
Age (years)		<0.0001			<0.0001
<11 years (reference)	–		–	–	
11-25 years	2.56 (2.53-2.60)		2.29 (2.25-2.33)	2.31 (2.27-2.34)	
26-40 years	4.21 (4.16-4.27)		3.90 (3.84-3.95)	3.92 (3.86-3.98)	
41-56 years	4.30 (4.24-4.36)		4.27 (4.20-4.33)	4.28 (4.22-4.35)	
≥57 years	5.52 (5.45-5.60)		4.97 (4.90-5.05)	4.97 (4.90-5.05)	
First Nations status		<0.0001			<0.0001
No (reference)	–		–	–	
Yes	0.87 (0.86-0.88)		0.91 (0.90-0.92)	0.90 (0.88-0.91)	
Charlson Comorbidity Index		<0.0001			<0.0001
0 (reference)	–		–	–	
1-2	1.66 (1.65-1.68)		1.55 (1.53-1.56)	1.55 (1.53-1.56)	
3-4	3.05 (2.98-3.12)		2.52 (2.47-2.58)	2.51 (2.45-2.57)	
5-6	3.65 (3.50-3.80)		3.26 (3.13-3.40)	3.25 (3.11-3.39)	
7-8	4.31 (4.08-4.54)		3.53 (3.35-3.73)	3.52 (3.34-3.72)	
9-10	4.33 (3.98-4.71)		3.34 (3.08-3.62)	3.34 (3.08-3.62)	
>10	5.12 (4.43-5.92)		4.36 (3.78-5.03)	4.39 (3.80-5.06)	
Location of residence		<0.0001			<0.0001
Urban (reference)	–		–	–	
Rural	0.91 (0.90-0.92)		–	0.93 (0.92-0.94)	
Missing	0.86 (0.85-0.86)		–	0.82 (0.81-0.84)	
Index of remoteness		<0.0001			<0.0001
<0.23 (reference)	–		–	–	
0.23-0.30	0.92 (0.91-0.93)		0.94 (0.93-0.95)	–	
0.31-0.40	0.87 (0.86-0.88)		0.86 (0.85-0.87)	–	
0.41-0.50	0.74 (0.73-0.75)		0.73 (0.72-0.75)	–	
0.51-0.60	0.68 (0.66-0.70)		0.78 (0.76-0.80)	–	
>0.60	0.71 (0.68-0.74)		0.87 (0.83-0.91)	–	
Missing	0.80 (0.76-0.85)		0.94 (0.89-1.00)	–	
Neighborhood income quintile		<0.0001			<0.0001
1 (reference)	–		–	–	
2	0.97 (0.96-0.98)		0.98 (0.97-1.00)	0.98 (0.97-1.00)	
3	1.01 (0.99-1.02)		1.02 (1.00-1.03)	1.01 (1.00-1.03)	
4	1.01 (1.00-1.02)		1.04 (1.02-1.05)	1.03 (1.02-1.05)	
5	1.00 (0.99-1.02)		1.04 (1.02-1.05)	1.03 (1.02-1.04)	
Missing	0.89 (0.88-0.90)		0.99 (0.98-1.01)	1.09 (1.07-1.11)	

* p-values from univariate models

† Model 1 includes the following variables: sex, age, First Nations status, Charlson Comorbidity Index, index of remoteness, and neighborhood income quintile (the variable location of residence is not included due to correlation between location of residence and index of remoteness).

‡ Model 2 includes the following variables: sex, age, First Nations status, Charlson Comorbidity Index, location of residence, and neighborhood income quintile (the variable index of remoteness is not included due to correlation between location of residence and index of remoteness).

§ p-values from both multivariate models

CI, confidence interval; IRR, incidence rate ratio.

category corresponding to Saskatoon and Regina, the largest urban centres in the province (aIRRs all <1.00; $p < 0.0001$; Table 5.5).

Figure 5.1 presents aIRRs for each census division in Saskatchewan, as well as all medium and large population centres in Saskatchewan, adjusted for sex, age, First Nations status, Charlson Comorbidity Index, and neighbourhood income quintile. Census divisions with low aIRRs approximate geographic areas with high index of remoteness values (Figure 5.2) and greater distance to and lower density of ultrasound facilities (Figure 2.2). Variation in aIRRs was observed across the four medium and large population centres, with aIRRs of 0.81 (95% CI, 0.80-0.82), 0.86 (95% CI, 0.84-0.88), and 0.86 (95% CI, 0.84-0.88) for Regina, Prince Albert, and Moose Jaw, respectively, relative to Saskatoon, the largest city in the province.

5.5 Discussion

An understanding of sociodemographic and geographic factors which are associated with ultrasound imaging utilization is critical in informing the provision of imaging services to more equitably serve the entire population. Variation in ultrasound utilization among sociodemographic groups and geographic regions may represent underutilization (secondary to barriers in accessing ultrasound services, for example) or overutilization (due to physician ordering practices, for example). Using a lens towards health equity, the root causes of variation should be carefully explored.

Lower rates of non-obstetrical ultrasound utilization in many remote areas of the province may reflect barriers which patients face in accessing ultrasound, such as the need to travel far distances—sometimes by plane—to reach an ultrasound facility.¹⁷¹ However, it is interesting that utilization rates did not continue to decrease with higher levels of geographic remoteness, but were lowest in mid-geographically remote areas.²⁰⁸ This may be explained by ultrasound and radiography being the most accessible imaging modalities in many rural and remote areas, leading physicians to order ultrasound imaging even in cases where another imaging modality

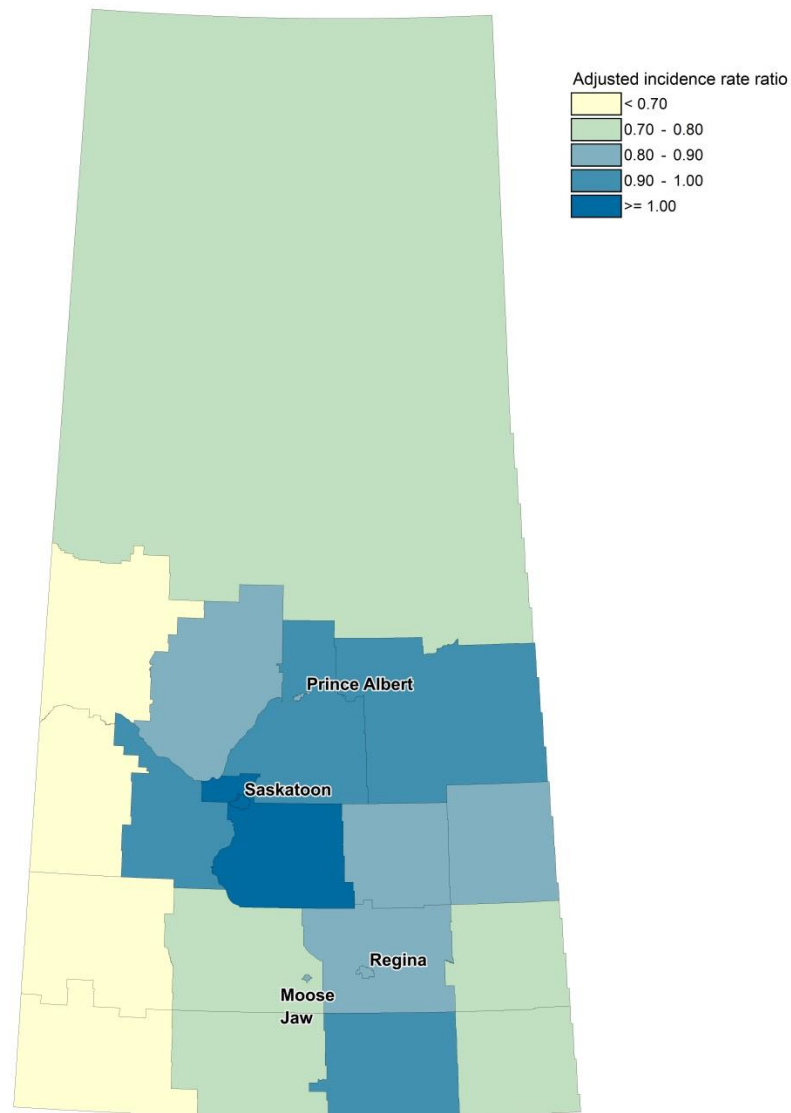


Figure 5.1. Choropleth map indicating adjusted incidence rate ratios of non-obstetrical ultrasound imaging utilization by census division in Saskatchewan. All 18 census divisions are outlined in grey, and all medium and large population centres (Saskatoon, Regina, Prince Albert, and Moose Jaw) are labeled. The reference category is Saskatoon, the largest population centre in the province. Incidence rate ratios were adjusted for sex, age, First Nations status, Charlson Comorbidity Index, and neighbourhood income quintile. Adjusted incidence rate ratios greater than 1 indicate higher rates of non-obstetrical ultrasound utilization relative to Saskatoon, and adjusted incidence rate ratios less than 1 indicate lower rates of utilization. Comparing Figures 5.1 and 5.2, areas which are more geographically remote generally have lower rates of non-obstetrical ultrasound utilization, and areas which are less geographically remote (surrounding medium and large population centres) generally have higher rates of non-obstetrical ultrasound utilization.

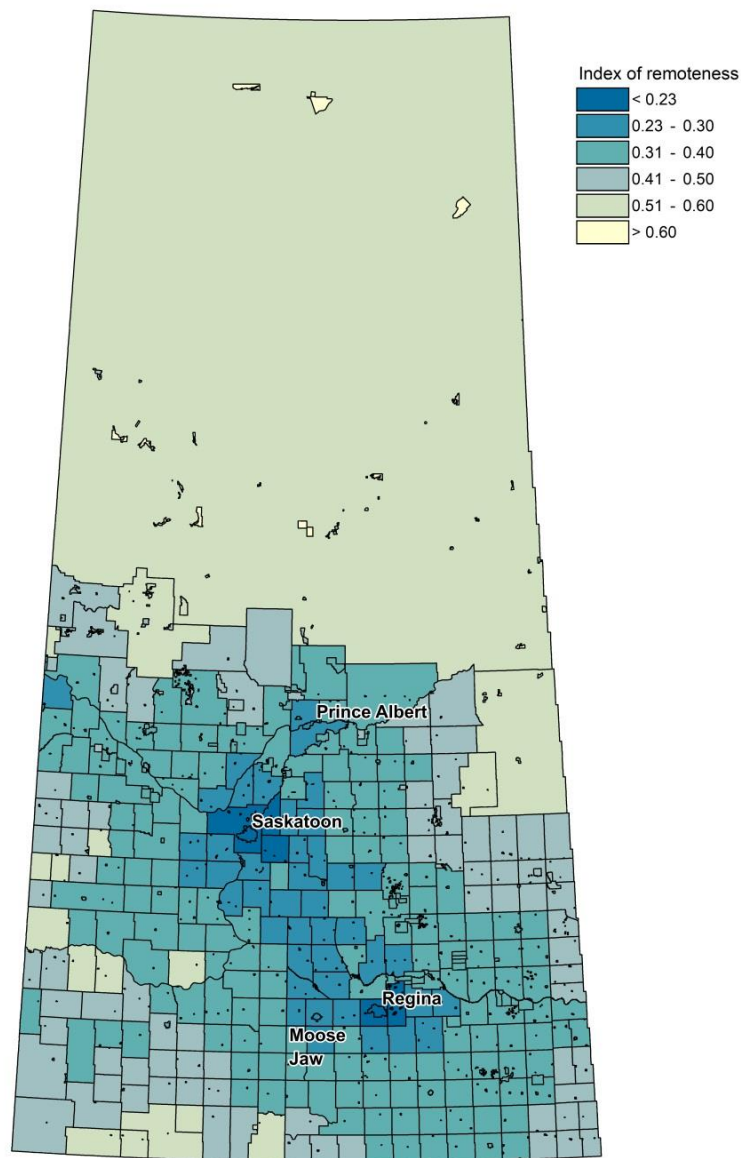


Figure 5.2. Choropleth map indicating index of remoteness values by census subdivision in Saskatchewan. Each census subdivision is outlined in black. Medium and large population centres (Saskatoon, Regina, Prince Albert, and Moose Jaw) are labeled. Index of remoteness values range from 0 (least geographically remote) to 1 (most geographically remote).

may be more appropriate. This explanation is supported by lower utilization rates of advanced imaging modalities across rural and remote regions in a Norwegian study.²¹⁷

Similar to prior studies,^{187,218–220} we found that higher neighbourhood income was associated with higher rates of ultrasound utilization. A previous study based in a single Canadian city found higher rates of diagnostic imaging (including non-obstetrical ultrasound, radiography, CT, and MRI) among patients in higher income neighbourhoods, though the effect size was larger than seen in our study, with relative risks ranging from 1.25–2.26 for highest vs. lowest neighbourhood income quintiles.¹⁸⁷ While the study did control for comorbidities and age, other variables, such as First Nations status, were not controlled for, potentially explaining the difference in effect size in our study.

Similar to our prior research which found that status First Nations individuals had a 20% lower rate of obstetrical ultrasound utilization,²⁰⁸ in this study we found that adjusted rates of non-obstetrical ultrasound utilization were 9-10% lower among status First Nations individuals. Differential rates of non-obstetrical ultrasound utilization among First Nations and non-First Nations individuals may be secondary to overutilization or underutilization of this imaging modality among population subgroups. However, Indigenous peoples face multiple barriers in accessing healthcare services, including racism, discrimination, and stereotyping in the healthcare system, sometimes leading to a reluctance to access healthcare services.^{18,19} In this context, these findings provide a call to action to address the barriers which Indigenous peoples face in accessing imaging to ensure equitable imaging utilization.

The magnitude of variation of ultrasound utilization across sociodemographic and geographic factors is substantial, and results can be used to inform ultrasound service planning. Based on Table 5.5, if the rate of ultrasound exams across the province were equal to the average rate of ultrasound exams in the two largest cities, an additional 13,023 exams would need to be performed over one year to compensate for areas with currently lower utilization rates. Similarly, if the rate of ultrasound exams across the province were equal to that of the index of remoteness level with the lowest adjusted rate of ultrasound exams, it could be considered that an “excess” of 35,234 exams are currently performed over one year across the province.

The use of innovative technologies such as telerobotic ultrasound should be explored to improve access to ultrasound services for underserved and marginalized populations and help minimize the degree of variation in ultrasound utilization in some rural and remote

areas.^{5,54,167,168} Other solutions, such as having an itinerant sonographer regularly travel to rural and remote communities, may also improve access to ultrasound services for these communities. Cultural safety training and ensuring culturally safe healthcare environments may increase the approachability, acceptability, and appropriateness of ultrasound services for Indigenous peoples, potentially reducing disparities in ultrasound utilization.

There are some limitations to this study. The CCI was used to control for comorbidities; however, as the index was initially designed to predict 1-year mortality risk, it may not directly relate to indications of a medically necessary ultrasound exam. However, it is reassuring that the CCI has been validated to predict individuals who will incur high healthcare costs,^{213,214} suggesting that is an effective measure to capture comorbidities that drive healthcare utilization. There are also a number of limitations inherent to the use of administrative data, including the potential for coding errors, incomplete data, and limitations in the variables available within administrative datasets. For example, First Nations status is based on self-reported data and accuracy is not verified by eHealth Saskatchewan. Additionally, data for location of residence (urban vs. rural) and neighbourhood income quintile were missing for a substantial proportion of individuals and were only available from January 2014 to October 2017. We used each individual's residence as of October 2017 to determine location of residence (urban vs. rural) and neighbourhood income quintile for the remainder of the study period; however, this may have resulted in non-differential misclassification for the small proportion of the population which moved between October 2017 and December 2018, potentially biasing towards the null for these variables. Finally, ultrasound exams performed at an imaging clinic in another province to which a Saskatchewan patient travels are generally covered by the home province through a reciprocal billing arrangement and are generally captured in Saskatchewan MSB physician billing data. However, exams performed at out-of-province hospitals are not captured in the provincial RIS and are not included in this study. This may result in slightly decreased ultrasound exam counts for patients living in communities near the provincial borders, such as for individuals in northeast Saskatchewan traveling to Flin Flon, Manitoba for an ultrasound exam.

In conclusion, this study highlights disparities in ultrasound utilization among specific sociodemographic and geographic groups, including individuals in low-income neighbourhoods, status First Nations individuals, and individuals in some rural and remote communities. Further work should explore solutions to minimize variation in ultrasound utilization between

sociodemographic and geographic groups, particularly among those who have known barriers in accessing ultrasound imaging, through the use of innovative technologies and programs.

5.6 Acknowledgements

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5.7 Disclosure

This study is based on de-identified data provided by the Saskatchewan Ministry of Health and eHealth Saskatchewan. The interpretation and conclusions contained herein do not necessarily represent those of the Government of Saskatchewan, the Saskatchewan Ministry of Health, or eHealth Saskatchewan.

CHAPTER 6

A CROSSOVER COMPARISON OF STANDARD AND TELEROBOTIC APPROACHES TO PRENATAL ULTRASOUND IMAGING*

Chapter 3 highlighted disparities in access to ultrasound imaging among northern, remote communities, and concluded that future efforts to improve access to imaging should consider barriers of distance to imaging facilities and strategies to bridge these barriers. Chapters 4 and 5 demonstrated substantial inequities in obstetrical and non-obstetrical ultrasound utilization, including among persons living in rural and remote communities, Indigenous persons, and persons living in low income neighbourhoods. Together these findings suggest an urgent need to explore solutions to improve access to ultrasound imaging in northern, remote communities.

Telerobotic ultrasound is a technology which allows a radiologist or sonographer to manipulate an ultrasound probe via a robotic arm, thereby remotely performing an ultrasound exam. This technology was selected for further investigation as a potential means of improving access to ultrasound imaging in northern, remote communities as it held potential to address many priorities and challenges identified in prior chapters: (1) using this technology, patients can receive ultrasound imaging in their home community, minimizing travel and its associated challenges, such as conflicting family and work responsibilities and travel expenses; (2) telerobotic technology may support decolonization of health systems in Indigenous communities, as the technology enables patients to connect with healthcare providers while they stay in their home community;^{30,33} and (3) sonographers or radiologists can perform exams from an urban centre, minimizing challenges associated with healthcare provider recruitment and retention in rural and remote communities.²⁴

As telerobotic ultrasound systems have evolved since early prototypes, it is critical to assess this technology and determine its current diagnostic capability and acceptability for clinical use. Drawing upon my work validating a telerobotic approach for abdominal ultrasound,⁵ and considering the substantial disparities in obstetrical ultrasound utilization presented in Chapter 4, Chapter 6 presents a clinical trial validating a telerobotic approach for obstetrical

* This chapter is based on:

Adams SJ, Burbridge BE, Badea A, Kanigan N, Bustamante L, Babyn P, Mendez I. A crossover comparison of standard and telerobotic approaches to prenatal ultrasound imaging. *J Ultrasound Med.* 2018;37(11):2603-2612. doi: 10.1002/jum.14619.

ultrasound. The study provides critical evidence paving the way for the deployment of telerobotic ultrasound systems in northern, remote communities as a means of improving access to ultrasound.

6.1 Abstract

Objective: To determine the feasibility of a telerobotic approach to remotely perform prenatal ultrasound examinations.

Methods: Thirty participants (mean gestational age, 22.9 ± 5.3 weeks) were prospectively recruited. Participants underwent a limited examination (assessing biometry, placental location, and amniotic fluid; $n = 20$) or a detailed examination (biometry, placental location, amniotic fluid, and fetal anatomic survey; $n = 10$) performed using a conventional ultrasound system. This was followed by an equivalent examination performed using a telerobotic ultrasound system which enabled sonographers to remotely control all ultrasound settings and fine movements of the ultrasound transducer from a distance. Telerobotic images were read independently from conventional images.

Results: Paired sample t-tests showed no statistically significant difference between conventional and telerobotic measurements of fetal head circumference, biparietal diameter, or single deepest vertical pocket of amniotic fluid; however, a small but statistically significant difference was observed in measurements of abdominal circumference and femur length (p -values <0.05). Intraclass correlations displayed excellent agreement (>0.90) between telerobotic and conventional measurements of all four biometric parameters. Of 21 fetal structures included in the anatomic survey, 80% of the structures attempted across all patients were sufficiently visualized using the telerobotic system (range 57-100% per patient). Ninety-seven percent of patients strongly or somewhat agreed they would be willing to have another telerobotic examination in the future.

Conclusions: A telerobotic approach is feasible for remotely performing prenatal ultrasound examinations. Telerobotic ultrasound (robotic telesonography) may allow for the development of satellite ultrasound clinics in rural, remote, or low-volume communities, thereby increasing access to prenatal imaging in underserved communities.

6.2 Introduction

Ultrasound imaging is unique as it is an operator-dependent modality, and the skills of the sonographer, radiologist, or obstetrician generating images are critical for diagnostic examinations. As a result, ultrasound imaging—including obstetrical ultrasound—is not readily

available in many communities across the developed and developing world due to a lack of on-site experts. In communities where obstetrical ultrasound imaging is not available, patients must often travel to another centre for imaging or forego prenatal imaging altogether, potentially compromising maternal and fetal safety. For patients requiring referral for subspecialized obstetrical ultrasound and residing in communities where basic ultrasound is available, travel to a tertiary care centre may still be required, which burdens patients and their families and may delay diagnosis and management.

Telerobotic ultrasound (robotic telesonography) has emerged as a potential solution to provide greater access to care for patients in communities in which basic or subspecialized ultrasound is not available, allowing patients to obtain these services in their home communities.^{5,221} Telerobotic ultrasound systems allow sonographers or radiologists at a central location to remotely manipulate a transducer and generate images in real-time via an internet connection. Our group recently assessed a telerobotic ultrasound system to remotely perform adult abdominal examinations. Sonographers based at our academic health sciences centre remotely scanned patients at an imaging clinic 2.75 km away.⁵ We concluded that a telerobotic ultrasound system is feasible for performing adult abdominal ultrasound examinations at a distant location, with minimal training and set-up requirements and a moderate learning curve.

An early telerobotic ultrasound system prototype showed promising results for obstetrical ultrasound. Arbeille et al. investigated a telerobotic ultrasound system to assess biometric parameters, placental location and amniotic fluid volume;¹²² however, the potential for the system to perform a fetal anatomical survey was not assessed. Additionally, this telerobotic ultrasound system did not allow users to remotely control settings such as gain or depth; rather, settings were controlled by an assistant at the patient's site.

Commercial-grade telerobotic ultrasound systems have now been developed, and a key prerequisite for widespread adoption of telerobotic ultrasound is systematic assessment of diagnostic capability and acceptability to users and patients.²²¹ In this study, the feasibility of using a 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) to perform routine prenatal ultrasound examinations

was assessed. An assessment of the acceptance of this system by users and patients was also performed.

6.3 Methods

6.3.1 Patient population

The study was approved by our institutional research ethics board. Patients 18 years and older scheduled for an obstetrical ultrasound examination at a local outpatient ultrasound clinic were prospectively recruited. Thirty patients (20 scheduled for a limited examination and 10 scheduled for a second-trimester fetal anatomical survey) were included in this study, including one patient with a twin pregnancy. The mean gestational age of all participants was 22.9 ± 5.3 weeks (range 15 to 36 weeks). The mean gestational age of the cohort of patients scheduled for a second-trimester fetal anatomical survey was 20.2 ± 1.0 weeks (range 19 to 23 weeks). Written informed consent was obtained from all participants.

6.3.2 Telerobotic System

A clinic room (serving as the patient-site/remote site) was equipped with the MELODY Patient System, SonixTablet ultrasound system and 5 MHz transducer. The MELODY Patient System is a three degrees of freedom robot designed to hold any standard ultrasound transducer, and allows users to remotely control rotation, rocking and tilting of the attached transducer.

An adjacent room (serving as the sonographer-site/central site) was equipped with the MELODY Expert System, consisting of a mock transducer and electronic control box. As sonographers manipulated the mock transducer in a manner similar to scanning conventionally, all fine movements of the mock transducer were reproduced by the scanning transducer at the patient-site via the three degrees of freedom robot. A touchscreen monitor at the sonographer-site displayed the identical ultrasound system interface to that displayed on the SonixTablet. Sonographers controlled all settings such as gain and depth and added image annotations using either the touchscreen monitor or mouse and keyboard.

A video conferencing system enabled communication between sonographers, patients and patient-site assistants. Gross placement of the robotic probe holder and pressure of the transducer on the patient were adjusted by patient-site assistants, who had no expertise in ultrasound, based on instructions from sonographers. A non-dedicated internet connection (50 Mbps download and

20 Mbps upload speed) connected the two sites, with separate data flows for the ultrasound video data, ultrasound settings, robotic control, and the videoconferencing system (Figure 6.1).

6.3.3 Scanning protocol

All patients were initially scanned using a conventional ultrasound system (EPIQ 5, Philips, Amsterdam, The Netherlands). Up to seven days (mean 2.0 days) following the conventional examination, patients were scanned by a different sonographer with similar experience and qualifications using the telerobotic system, blinded to the findings of the conventional examination. Based on the referring clinician's initial request, examinations included biometry (biparietal diameter, head circumference, abdominal circumference, and femur length), amniotic fluid volume, and placental location ($n = 20$) or a complete screening examination including fetal anatomy based on the Society of Obstetricians and Gynaecologists of Canada's clinical practice guideline "Content of a Complete Routine Second Trimester Obstetrical Ultrasound Examination and Report" ($n = 10$).²²² The duration of each exam was recorded. Two sonographers performed all 30 conventional examinations (performing 14 and 16

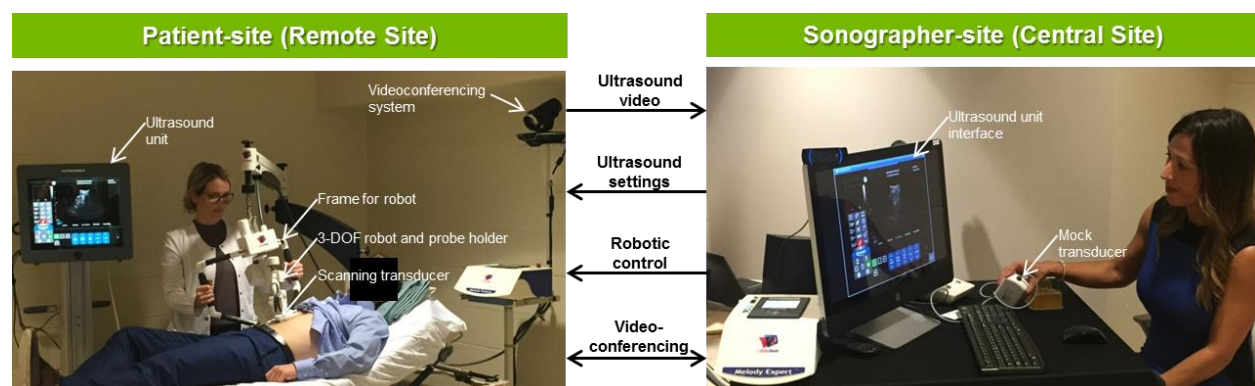


Figure 6.1. Telerobotic ultrasound system used to perform obstetrical ultrasound exams. At the patient-site, an assistant holds the frame for a three-degrees-of-freedom (DOF) robot to which the scanning transducer is attached. A videoconferencing system allows the sonographer and the patient to communicate with each other, and allows the sonographer to provide instructions to the patient-site assistant regarding gross placement of the frame for the robot. At the sonographer-site, a sonographer manipulates a mock transducer, and all movements of the mock transducer (rotation, rocking, tilting) are directly replicated by the scanning transducer at the patient-site. Real-time ultrasound video data and a user interface identical to that of the ultrasound unit is displayed at the sonographer-site, and the sonographer can remotely control all settings on the ultrasound unit. A non-dedicated internet connection connects the two sites, with separate data flows for ultrasound video, ultrasound settings, robotic control, and videoconferencing.

examinations, respectively) and the same two sonographers performed all telerobotic examinations (performing 16 and 14 examinations, respectively). There were two patient-site assistants who assisted with 7 and 23 telerobotic examinations, respectively.

6.3.4 Image interpretation

Images from telerobotic examinations were read independently from images from conventional examinations by a single board-certified radiologist, blinded to findings of the corresponding examination. A standardized reporting form was used to assess whether structures could be sufficiently visualized on telerobotic and conventional examinations.

6.3.5 Patient assessment

Following completion of both scans, patients completed a survey based on Adams et al.⁵ regarding their experience with the telerobotic examination. Participants were asked to indicate their agreement using a 5-point Likert scale with the following four 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 video conferencing 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.

6.3.6 Sonographer and patient-site assistant assessment

Similarly, sonographers were asked to indicate their agreement with the following statements using a 5-point Likert scale following each telerobotic examination: (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 ultrasound. Patient-site assistants indicated their 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 (i.e. I felt tired or sore as a result of holding the MELODY system).⁵

6.3.7 Statistical analysis

Statistical analysis was performed using SPSS Statistics version 23.0 (IBM, Armonk, NY). Descriptive statistics, including mean values, standard deviations, and mean differences for continuous variables and frequencies and proportions for categorical responses, were determined. Measurements of structures from conventional and telerobotic exams were compared using a paired sample t-test and agreement was assessed using intraclass correlation coefficients. A p-value of less than 0.05 was regarded as significant.

6.4 Results

6.4.1 Image assessment

Paired sample t-tests showed no statistically significant difference between conventional and telerobotic measurements of fetal head circumference, biparietal diameter, or single deepest vertical pocket of amniotic fluid; however, a small but statistically significant difference was observed in measurements of abdominal circumference and femur length (p-values <0.05). Intraclass correlations displayed excellent agreement between telerobotic and conventional measurements of all four biometric parameters (Table 6.1). In 13 (43%) cases the relationship

Table 6.1. Comparison of measurements as determined using telerobotic and conventional ultrasound

Measurement	Telerobotic mean measurement ± SD	Conventional mean measurement ± SD	n*	Mean difference (95% CI)†	p- value‡	ICC
Biparietal diameter (mm)	54.9 ± 15.9	54.1 ± 16.4	31	0.8 (-0.4, 1.7)	0.05	0.995
Head circumference (mm)	204.5 ± 56.3	202.9 ± 58.3	30	1.6 (-2.2, 4.4)	0.27	0.995
Abdominal circumference (mm)	188.9 ± 64.7	184.6 ± 65.3	31	4.2 (-0.1, 8.2)	0.02	0.993
Femur length (mm)	40.7 ± 14.0	39.1 ± 13.5	31	1.7 (0.5, 2.2)	<0.001	0.990
Amniotic fluid – single deepest pocket (mm)	49.0 ± 14.9	48.7 ± 11.4	24	0.21 (-5.2, 5.6)	0.94	0.711

* number of paired robotic-conventional assessments

† robotic measurement minus conventional measurement

‡ paired t-test

CI, confidence interval; ICC, intraclass correlation coefficient; SD, standard deviation.

between the placenta and internal cervical os was not adequately demonstrated on telerobotic images.

Of 21 fetal structures included in the fetal anatomic survey, 80.0% of all structures attempted across patients (range 57-100% per patient) were satisfactorily demonstrated using the telerobotic system, in comparison to 98.6% (range 86-100% per patient) on conventional examinations. The cranium, stomach, bladder, abdominal umbilical cord insertion, upper extremities, and lower extremities were successfully demonstrated on all telerobotic examinations; however, the cavum septi pellucidi and cardiac outflow tracts were demonstrated in less than 50% of examinations (Table 6.2). All findings (two echogenic foci within the left ventricle) identified on conventional ultrasound were also detected by sonographers using the telerobotic ultrasound system. Representative images from telerobotic and conventional ultrasound systems are presented in Figures 6.2 and 6.3.

6.4.2 Patient assessment

Most participants somewhat or strongly agreed that they felt comfortable communicating with the remote sonographer using the video conferencing system, felt comfortable knowing that a person in a different room was controlling the ultrasound probe, and perceived less abdominal pressure during telerobotic examinations than during conventional exams (Table 6.3). Ultimately, 97% of patients agreed they would be willing to have another telerobotic examination in the future if conventional ultrasound was not available in their community.

6.4.3 Sonographer and patient-site assistant assessment

The average duration of second-trimester fetal anatomical survey examinations performed telerobotically was 27.8 ± 4.3 minutes (range 23 to 35 minutes), similar to that of examinations performed conventionally (27.8 ± 7.9 minutes, range 23 to 35).

The audio quality using the TE30 All-in-One, HD Videoconferencing Endpoint was sufficient to allow sonographers and the patient-site assistant to communicate regarding gross placement of the robotic probe holder and patient positioning (Table 6.3). Strategies used to communicate with the patient-site assistant regarding gross placement of the robotic probe holder included using simple terms such as “up”, “down”, “right” or “left” relative to the umbilicus or pubis, and reorienting using the pubic symphysis as a landmark when contact was lost. Sonographers generally reported that manipulating the mock transducer resulted in less physical

Table 6.2. Visualization of fetal anatomy using telerobotic and conventional ultrasound

	Telerobotic			Conventional		
	Sufficiently visualized (n)	Attempted (n)	Percent visualized	Sufficiently visualized (n)	Attempted (n)	Percent visualized
Cranium	10	10	100%	10	10	100%
Cerebral ventricles	8	9	89%	10	10	100%
Cavum septi pellucidi	3	9	33%	10	10	100%
Midline falx	9	10	90%	10	10	100%
Choroid plexus	9	10	90%	10	10	100%
Cisterna magna	9	10	90%	10	10	100%
Cerebellum	9	10	90%	10	10	100%
Orbits	9	10	90%	9	10	90%
Lips	5	10	50%	9	10	90%
Spine	5	9	56%	10	10	100%
Chest	5	8	63%	10	10	100%
Cardiac four- chamber view	8	10	80%	10	10	100%
Cardiac outflow tracts	4	10	40%	9	10	90%
Heart axis	8	10	80%	10	10	100%
Cardiac situs	7	10	70%	10	10	100%
Stomach	10	10	100%	10	10	100%
Kidneys	5	9	56%	10	10	100%
Bladder	9	9	100%	10	10	100%
Abdominal umbilical cord insertion	10	10	100%	10	10	100%
Upper extremities and presence of hands	10	10	100%	10	10	100%
Lower extremities and presence of feet	9	9	100%	10	10	100%

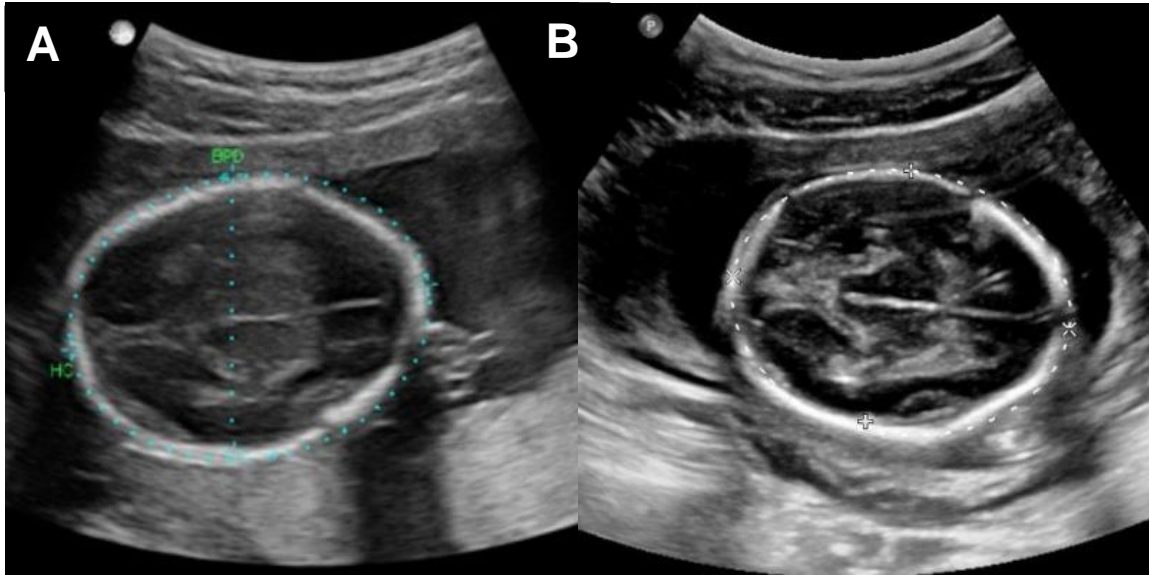


Figure 6.2. Representative ultrasound images demonstrating equivalence of measurement of biparietal diameter and head circumference using the (A) telerobotic ultrasound system and (B) conventional ultrasound system.

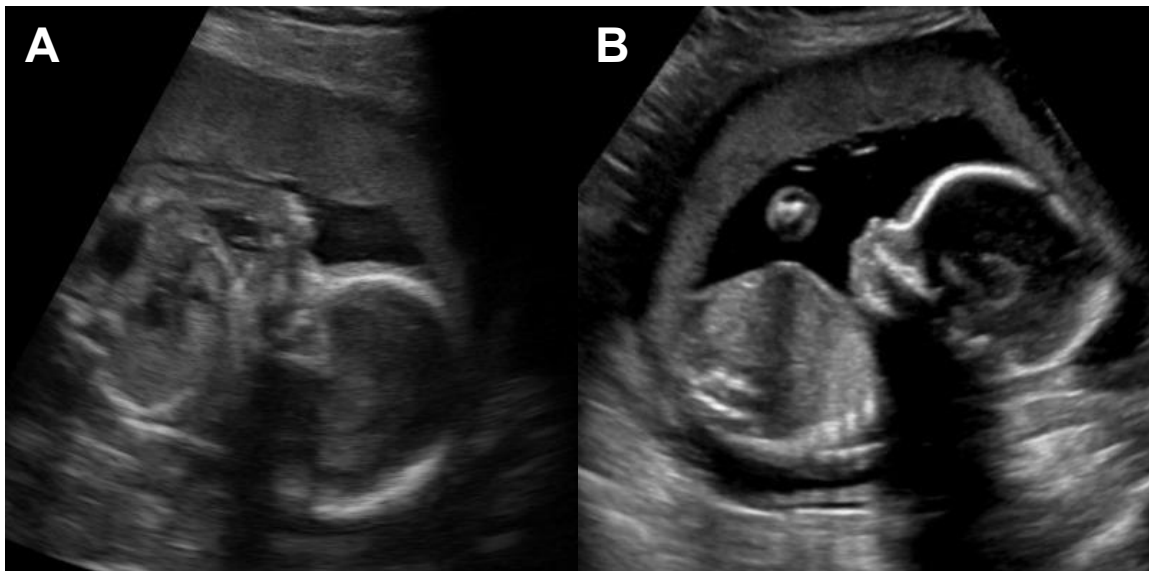


Figure 6.3. Representative images demonstrating fetal profile using the (A) telerobotic ultrasound system and (B) conventional ultrasound system. Ultrasound exams were performed at 20 weeks 4 days and 20 weeks 0 days, respectively.

Table 6.3. Survey responses from patients, sonographers, and patient-site assistants following telerobotic exams

	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	26 (90)	2 (7)	0 (0)	0 (0)	1 (3)
(2) I felt comfortable communicating with the remote sonographer using the video conferencing system	25 (86)	3 (10)	0 (0)	0 (0)	1 (3)
(3) I felt comfortable knowing that a person in a different room was controlling the ultrasound probe	23 (79)	2 (7)	3 (10)	0 (0)	1 (3)
(4) I felt less pressure on my abdomen during the robotic telesonography study than I did during the conventional study	13 (45)	11 (38)	3 (10)	2 (7)	0 (0)
Sonographers					
(1) The audio was of sufficient quality to allow me to adequately communicate with the patient-site assistant	21 (72)	8 (28)	0 (0)	0 (0)	0 (0)
(2) The patient-site assistant and I were able to effectively communicate regarding probe or patient positioning	11 (38)	12 (41)	1 (3)	4 (14)	1 (3)
(3) Manipulating the remote ultrasound probe resulted in less physical strain than scanning a similar patient using conventional sonography	13 (45)	13 (45)	2 (7)	1 (3)	0 (0)
Patient-site assistant					
(1) The audio was of sufficient quality to allow me to adequately communicate with the remote sonographer	20 (71)	8 (29)	0 (0)	0 (0)	0 (0)
(2) The sonographer and I were able to effectively communicate regarding probe or patient positioning	15 (54)	11 (39)	0 (0)	2 (7)	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)	0 (0)	6 (21)	5 (18)	13 (46)	4 (14)

Data are presented as n (%).

strain than scanning a patient with a similar body habitus using a conventional ultrasound system. However, the patient-site assistant reported that holding and grossly positioning the frame for the robotic arm caused moderate or severe physical strain in several cases (Table 6.3).

6.5 Discussion

Access to prenatal imaging has been identified as an especially important need in communities which lack imaging facilities. As obstetrical ultrasound is not available in many rural and remote communities, patients must travel or be transported to larger centres for imaging, resulting in additional transportation costs and delays in management. Due to the inconvenience and financial cost of transportation and loss of work time, many patients may forego prenatal imaging. In this study we demonstrated the feasibility of using a telerobotic approach to remotely perform prenatal ultrasound imaging studies. Biometric measurements obtained using the telerobotic ultrasound examination showed excellent agreement with conventional examinations. Patients readily accepted the technology and would be willing to have another exam performed telerobotically in the future. However, our study also demonstrated some limitations in the telerobotic ultrasound system's ability to currently demonstrate all fetal anatomy required for a second-trimester fetal anatomical survey in some patients.

While our analysis demonstrated a statistically significant difference between measurements of the abdominal circumference and femur length when measured telerobotically as compared to the reference standard, there is a lack of consensus on what defines a clinically meaningful difference. In a study comparing 3D ultrasound measurements to those generated using traditional 2D ultrasound, a statistically significant difference was observed in measurements of head circumference, abdominal circumference, and femur length. However, the authors concluded that these did not represent meaningful, clinically relevant differences; this was supported by intraclass correlation coefficients indicating excellent agreement between the two techniques.²²³ Further, it is established in the literature that there is a high interobserver variability of measurements of the single deepest vertical pocket of amniotic fluid; for example, Sande et al. found an interobserver variability of -51% to 52% (95% confidence interval),²²⁴ consistent with the greater variability between telerobotic and conventional measurements of this variable in our study.

Structures which were least reliably visualized telerobotically in our study included the cavum septi pellucidi, cardiac outflow tracts, spine, and kidneys. Further, determination of cardiac situs was appropriately documented in only 70% of cases, as documentation of both an axial view of the upper abdomen and four-chamber view of the heart were required for assessment to be considered adequate. These correspond to structures which are generally most difficult to satisfactorily demonstrate conventionally. For example, in a series of 98 patients at 18 and 22 weeks gestational age, cardiac views were adequately obtained in only 80.6% to 83.7% of patients and the spine was adequately demonstrated in only 85.7% to 86.7% of patients using conventional ultrasound.²²³ We hypothesize that in a clinical setting, where demonstrating all fetal structures may be of critical importance for patient management, visualization scores may improve with additional time taken to demonstrate all fetal structures. Due to the difficulty in visualizing the right and left ventricular outflow tracts, the addition of a three-vessel and tracheal view may be an especially important addition to telerobotic ultrasound protocols. This view is generally easier to acquire in first, second and third trimester studies and has been reported to be helpful for detecting most ductal-dependent cardiac malformations.²²⁵ Additionally, use of three-dimensional (3D) ultrasound—which allows a user to obtain a series of volumes that can later be displayed and reconstructed in any plane—may offer improved visualization of structures poorly visualized using two-dimensional (2D) telerobotic scanning. Benacerraf et al. found that a standard fetal anatomic survey can be performed in 1.8 minutes by acquiring five 3D volumes (compared to 19.6 minutes using a standard 2D approach), with visualization of structures ranging from 92-100%.²²⁶ However, structures that were poorly visualized in our study, such as the cavum septi pellucidi and the cardiac outflow tracts, were some of the same structures which were least well visualized on 3D ultrasound volumes.²²⁶ Nevertheless, it is plausible that 3D volumes could be acquired in a short amount of time remotely using a telerobotic ultrasound system or by a trained patient-site assistant; this may offer additional diagnostic information beyond that provided by 2D image acquisitions. Obtaining cine clips through structures which are difficult to capture may also allow for improved diagnosis by the radiologist. Further, as the relationship between the cervical os and placenta was not consistently demonstrated in our study due to the robotic arm frame and pubic symphysis preventing the required angulation to be obtained, training the patient-site assistant to manually scan this region with real-time, remote

guidance from the sonographer may be a potential solution to improve visualization of this important relationship.

Most of the literature surrounding teleultrasound considers only the transmission of images generated directly at the patient's location for remote interpretation,^{227–229} and there is limited literature describing telerobotic approaches for performing obstetrical examinations.²³⁰ Arbeille et al.¹²² found that in 93.1% of cases biometric parameters, placental location and amniotic fluid volume were correctly assessed using a telerobotic ultrasound system. While visualization of additional fetal anatomic structures was attempted using the telerobotic ultrasound system, these were not included in the visualization score. Similar to our group's previous study evaluating telerobotic abdominal examinations,⁵ Arbeille et al. found that the duration of telerobotic examinations was longer than that of conventional examinations (18 minutes compared to 14 minutes). The relatively decreased time requirement for telerobotic examinations in this study (such that telerobotic and conventional examinations were of the same duration) may be attributed to sonographers' additional experience using the telerobotic system prior to the commencement of the patient recruitment, as well as the enhanced functionality of the telerobotic system allowing the sonographer to remotely control ultrasound settings and annotate images, an improvement over the telerobotic ultrasound system used by Arbeille et al.¹²²

This study also identified potential improvements to telerobotic ultrasound systems, including the ability for the sonographer to control translational movements and pressure of the transducer, modifications of the frame for the robotic arm to reduce strain for patient-site assistants, and the development of a smaller base for the probe holder, as sonographers noted that some angles were difficult to obtain due to the footprint of the probe holder, which may be a reason that some structures such as the internal cervical os could not be sufficiently demonstrated in all cases.

An alternate system consisting of a probe outfitted with one motor to tilt the transducer and a second motor to rotate the probe around its central axis has also been assessed by a group in France for telerobotic obstetrical examinations. Following 15 obstetrical examinations, the authors reported that telerobotic images were of similar quality to that generated using a robotic arm similar to the MELODY system; however, no formal evaluation methods were reported and the scope of the obstetrical examinations performed is unclear.⁶²

The performance of ultrasound studies by midwives has been identified as another potential solution to increase access to ultrasound in some communities, especially in countries with a greater number of midwives or nurses than sonographers. For example, a pilot project in Kenya trained midwives to perform basic obstetrical ultrasound and then transmit images and preliminary reports from three clinics via a 3G mobile phone network for radiologists to review at a Kenyan hospital 20-, 120- and 400-km away, respectively.²³¹ The study found excellent correlation between outcomes of the pregnancies and diagnoses based on preliminary reports generated by midwives. While this represents a potential solution to increase access to ultrasound in some communities, the substantial training period required for midwives to gain competence in scanning (training 8 hours per day for four weeks) and the inability for radiologists to confirm findings through real-time ultrasound video transmission or scanning themselves are drawbacks of this process. The role of midwives in performing ultrasound in developed countries is variable according to local laws, and it is considered within the scope of midwifery practice for midwives to perform point-of-care ultrasound.²³² However, midwives who perform advanced ultrasound studies such as fetal anatomic surveys generally hold a sonographer designation,²³² and access to ultrasound imaging remains limited in many communities.

Unique strengths of this study include that patients were recruited prospectively, sonographers were blinded to findings of the corresponding examination, a standardized imaging protocol was used for all examinations, a full prenatal examination based on established clinical practice guidelines was performed, and all examinations were reported using a standardized reporting form. There are also some limitations to this study. All telerobotic examinations were performed after the conventional study, resulting in some patients not being able to tolerate the entirety of the second scan due to time constraints or discomfort. In such cases, structures which were not attempted due to time factors were not included in data analysis. While 15 telerobotic examinations were performed the same day as conventional examinations, 15 telerobotic examinations were performed up to seven days after the conventional study, resulting in the potential for changes in fetal position or lie, fetal growth, and changes in biometric parameters over this time period. Finally, differences in diagnostic performance may partly be attributable to the quality of the ultrasound systems (EPIQ 5 and SonixTablet). Additional research utilizing the SonixTablet for both telerobotic and conventional examinations may be helpful to differentiate differences due to the method of scanning (telerobotic or conventional) versus the quality of the

ultrasound system. However, the design of this study allowed us to compare the telerobotic ultrasound system to a conventional system commonly used in larger centres, thus comparing it to a gold standard.

We plan to establish a pilot robotic ultrasound clinic in an underserved remote community in northern Canada to provide obstetrical and abdominal examinations. Establishing this service in a geographical area where there is a critical gap of obstetrical ultrasound access will allow us to assess the impact of this technology in prenatal care. Our vision is to establish a network of telerobotic ultrasound systems in rural, remote, and low-volume centres—established in partnership with local communities—which will be serviced by central radiology groups. Ultimately, telerobotic ultrasound has the potential to provide increased access to imaging and greater equity in the delivery of healthcare services, enabling pregnant women to access prenatal imaging in their home community.

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CHAPTER 7

A TELEROBOTIC ULTRASOUND CLINIC MODEL OF ULTRASOUND SERVICE DELIVERY TO IMPROVE ACCESS TO IMAGING IN NORTHERN, REMOTE COMMUNITIES*

Chapter 6 demonstrated that a telerobotic approach is feasible for remotely performing obstetrical ultrasound exams. Combined with our previous study validating a telerobotic approach for performing abdominal ultrasound exams,⁵ these results provide confidence in deploying this technology in northern, remote communities to increase access to ultrasound imaging and address disparities in ultrasound utilization as shown in prior chapters.

This chapter describes our experience establishing telerobotic ultrasound clinics in three northern, remote communities in Saskatchewan, the first telerobotic ultrasound clinics in North America. The chapter presents a mixed-methods study evaluating 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. The study's findings may inform the spread and scale of integrating telerobotic ultrasound into an ultrasound service delivery model to improve access to ultrasound imaging in underserved communities.

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7.1 Abstract

Objective: Patients living in many rural and remote areas do not have readily available access to ultrasound services due to 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 diagnostic ultrasound access to rural and remote communities.

Methods: Telerobotic ultrasound clinics were developed in three remote communities more than 500 km away from our academic medical centre. Sonographers remotely performed all ultrasound exams using telerobotic ultrasound systems and exams were subsequently interpreted by radiologists at an academic medical centre. 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 exams were remotely performed and included in this study, with the most frequent exam types being abdominal ($n = 35$), first trimester obstetrical ($n = 26$), and second trimester complete obstetrical ($n = 12$). Across all exam types, 70% of telerobotic ultrasound exams 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 exam 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.

7.2 Introduction

Access to healthcare services, including medical imaging, is an important determinant of health.⁴ Challenges in accessing healthcare services can result in delays in diagnosis and treatment, development of advanced disease, and higher rates of complications.¹³² Although medical imaging services are widely available in most urban centres, access is limited in many

rural and remote communities around the world.^{1,138} Availability of ultrasound services in rural and remote communities is challenged by difficulty recruiting sonographers to these communities, and due to 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 centre with ultrasound services available is hundreds of kilometres away. Family and work responsibilities complicate travel to another community for an ultrasound exam, with patients often having to leave their family behind and find reliable childcare when traveling to another community for an ultrasound exam. In communities which have an itinerant sonographer who periodically visits the community, patients experienced long wait times for an ultrasound exam. In some cases the many challenges patients faced in accessing ultrasound services led them to choose to not proceed with an ultrasound exam, resulting in a missed opportunity to provide clinically appropriate care.¹⁷¹ Many rural and remote communities have a large proportion of Indigenous peoples, who experience lower health outcomes relative to non-Indigenous peoples;¹⁶² 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 which 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 exam.¹⁶⁷ In communities where sonographers are not available on-site, telerobotic ultrasound provides an opportunity for sonographers to remotely *perform* the exam, as well as for radiologists to remotely *interpret* the exam. This is in contrast to teleradiology, which only allows radiologists to remotely interpret exams and is reliant on a sonographer physically being present at the facility where the patient is in order to perform the exam. Prior clinical trials comparing telerobotic ultrasound to conventional ultrasound have demonstrated the feasibility of using telerobotic ultrasound to remotely perform abdominal and obstetrical exams.^{5,54} This technology holds the potential to allow patients to stay in their home community for an ultrasound exam, while improving patient access to imaging expertise at larger centres.

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 paper, 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.

7.3 Methods

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

7.3.1 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 243, 2,372, and 1,942 people, respectively, although health centres in these communities also serve neighbouring 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 one 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 centres which 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 COVID-19 pandemic due to a severe COVID-19 outbreak. During

this lockdown, the telerobotic ultrasound service provided diagnostic ultrasound exams 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 healthcare services in their community. The third community had not yet established a telerobotic ultrasound clinic during the early months of the COVID-19 pandemic.

7.3.2 Clinic set-up

Telerobotic ultrasound systems were transported to and set-up at health centres 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 (Figure 7.1). 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) was 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 centre. Driving distances from the sonographer-sites to the patient-sites were approximately 1041 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 exam could also view images in real-time using Tixeo Communication Client.

Bandwidth was 20 Mbps (symmetric), 5 Mbps (symmetric), and 50 Mbps (symmetric) in Community A, B, and C, respectively. Bandwidth at the sonographer-site was 20-25 Mbps (symmetric). This was well above the minimum recommended bandwidth for the telerobotic



Figure 7.1. Representative telerobotic ultrasound system used at three northern Saskatchewan clinics. (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 (3-DOF) 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-DOF 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.

ultrasound system, which is 100 Kbps for robotic control data, 1 Mbps (symmetric) for video conferencing data, and 1.5 Mbps (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 exams, 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 prior to patients being 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.

7.3.3 Image acquisition

Participant inclusion criteria for the study were patients referred for an abdominal, pelvic, or obstetrical ultrasound exam by their local physician. Exclusion criteria included patients who did not provide consent to have a telerobotic ultrasound exam 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 exams scheduled on any given day. Sonographers used a telerobotic ultrasound system to remotely perform all ultrasound exams. Sonographers remotely performed all ultrasound exams as requested by the referring clinician based on routine imaging protocols for abdominal exams,²³³ first trimester obstetrical exams,²³⁴ second trimester complete obstetrical exams,¹³⁶ pelvic exams,²³⁵ and renal exams (including assessment of the kidneys and bladder). Limited obstetrical exams included assessment of fetal anatomy not well assessed on the initial second trimester fetal anatomic survey, amniotic fluid volume, fetal presentation, and/or fetal biometry, as requested by the referring clinician. All pelvic and obstetrical exams were performed transabdominally, and endovaginal scanning was not performed. The duration of each exam (from the times the first and last images were obtained) was recorded.

Sonographers completed a data collection form after each telerobotic ultrasound exam, including a series of Likert items describing their experience communicating with the patient and patient-site assistant, technical challenges encountered during the telerobotic ultrasound exam,

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 exam.

7.3.4 Image assessment

Images from all telerobotic ultrasound exams were read by one of two board-certified radiologists with seven and 31 years' experience, respectively, interpreting ultrasound. Images were archived on a province-wide picture archiving and communication system (PACS) and reported using the same workflow as exams performed locally. Reports were distributed using existing processes for exams entered in the province-wide radiology information system (RIS). 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 exam.

7.3.5 Assessment of patient experience

Following each ultrasound exam, patients were invited to complete a survey including Likert items based on a previously developed survey.^{5,54} 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."¹⁶⁸

Free-text responses from patient surveys were analysed using thematic analysis.²³⁶ A standard procedure for thematic analysis was followed based on Braun et al.²³⁶ Two team members familiarized themselves with survey responses, generated initial codes, and generated and revised themes in a reflexive and recursive process.²³⁶

7.3.6 Workflow challenges and solutions

Challenges and solutions observed throughout the process of deploying telerobotic ultrasound systems and performing telerobotic ultrasound exams 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.

7.3.7 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 standard deviations (or medians and interquartile ranges) were determined for continuous variables.

7.4 Results

7.4.1 Demographic and exam information

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

Eighty-seven exams were performed, including 41 in Community A, 36 in Community B, and 10 in Community C. Exams 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 ($n = 2$) exams (Table 7.1). A subset of obstetrical exams performed in one of the communities was previously reported in a paper describing our team's experience deploying a telerobotic ultrasound system during a COVID-19 outbreak¹⁶⁸. Average (\pm standard deviation) duration of each telerobotic ultrasound exam was 26 (± 8) minutes for abdominal exams, 12 (± 7) minutes for first trimester obstetrical exams, 35 (± 10) minutes for second trimester complete obstetrical exams.

Latency between movement of the mock probe and resulting change in the ultrasound image was noted by sonographers in 11 (13%) exams. Sonographers also noted difficulty synchronizing the orientation of the mock probe to the scanning probe in 3 (3%) exams. Intermittent loss of control of the scanning probe was experienced in 2 (2%) exams. While audio quality was sufficient for sonographers and patient-site assistants to communicate with each other for almost all exams (Table 7.2), in 5 (6%) exams 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

Table 7.1. Telerobotic ultrasound exams performed

Type of exam	n	Average duration (\pm SD), minutes	Image adequacy, n (%)			Conventional exam recommended, n (%)
			Adequate	Adequate with some reservations	Inadequate	
Abdominal	35	26 (\pm 8)	15 (43)	11 (31)	9 (26)	9 (26)
First trimester obstetrical	26	12 (\pm 7)	16 (62)	5 (19)	5 (19)	5 (19)
Second trimester obstetrical (complete)	12	35 (\pm 10)	2 (17)	3 (25)	7 (58)	9 (75)
Limited obstetrical	8	17 (\pm 8)	6 (75)	1 (13)	1 (13)	1 (13)
Pelvic	4	11 (\pm 5)	2 (50)	0 (0)	2 (50)	2 (50)
Renal	2	17 (\pm 1)	2 (100)	0 (0)	0 (0)	0 (0)

SD, standard deviation.

Table 7.2. Patient and provider experiences during telerobotic ultrasound exams

	Strongly agree, n (%)	Somewhat agree, n (%)	Neither agree nor disagree, n (%)	Somewhat disagree, n (%)	Strongly disagree, n (%)
A. Patients					
(1) I would be willing to have another telerobotic ultrasound exam if I required another ultrasound exam 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)
B. 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)
C. 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)

new patient-site assistant without as much experience assisted with the telerobotic ultrasound exams.

7.4.2 Image assessment

Across all exam types, radiologists determined 43 (49%) telerobotic ultrasound exams as adequate for diagnosis, 20 (24%) adequate with some reservations, and 24 (28%) as inadequate for diagnosis (Table 7.1). Representative images obtained using telerobotic ultrasound systems are provided in Figure 7.2. The proportion of exams for which a radiologist subsequently recommended a follow-up conventional ultrasound to clarify findings on the telerobotic ultrasound exam ranged from 0% for renal exams to 75% for second trimester complete obstetrical ultrasound exams (Table 7.1). Based on the high rate of second trimester obstetrical ultrasound exams which were recommended to be repeated as all anatomy could not be adequately assessed, part way through the study it was decided that these exams would not continue to be performed using the telerobotic ultrasound system.

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

7.4.3 Patient experience

Ninety-five percent of patients indicated they would be willing to have another telerobotic ultrasound exam in the future (Table 7.2). Four themes were identified regarding patients' experiences during telerobotic ultrasound exams:

- 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 exams, 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 to their prior experiences having ultrasound exams; and



Figure 7.2. Representative images obtained using telerobotic ultrasound systems. (A) 76-year-old male 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) 23-year-old female 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) 34-year-old female referred for a second trimester complete obstetrical exam. The exam was limited due to 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 exam.

- 4) Increased safety during the COVID-19 pandemic, as the technology allowed patients to stay in their own community and receive care from healthcare providers from their own community, minimizing spread of SARS-CoV-2.

7.4.4 Workflow challenges and solutions

Challenges and solutions from our experience developing three telerobotic ultrasound clinics in northern, remote, Indigenous communities are summarized in Table 7.3. Operational challenges were related to technical infrastructure, human resources, and coordination between clinic sites.

7.5 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 exams 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 towards 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.¹⁷¹ Other factors, including work and family responsibilities, were exacerbated by geographic remoteness, as an ultrasound appointment that might otherwise take two hours for a patient residing in a city might take two days or more for a patient living in a remote community who must travel long distances to an ultrasound facility.¹⁷¹ Minimizing distance from ultrasound services is critical to ensure equitable access. Telerobotic ultrasound clinics may be an important step towards reducing disparities in access to care and health outcomes between urban and rural/remote populations. Indeed, one of the main themes which 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 exams. While at this point we have not developed an after-hours (on-call) telerobotic ultrasound service, in the future this may be

Table 7.3. 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.
Set-up 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 back-up coverage available if one technician is away. Develop a strong working relationship with the vendor to troubleshoot any issues which 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 exams 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 exam requisitions	Clearly define the types of exams which can be facilitated using the telerobotic ultrasound system. For example, practices may wish to specify that pelvic and second trimester obstetrical exams should not be performed telerobotically. Ensure a lead sonographer screens exam requisitions before they are scheduled to help ensure all exams are successfully completed.

IT, information technology; PACS, picture archiving and communication system; RIS, radiology information system.

considered to better serve rural and remote communities. In 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.¹⁶⁸

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.^{4,7,15,20} Remote presence and virtual care technologies are considered a culturally safe method of providing care to Indigenous communities, as it allows patients to stay in their home communities.³³ Our study suggests that telerobotic ultrasound is well accepted by most patients, though a few patients expressed some initial apprehension with the technology, reporting that the ultrasound exam “didn’t seem real.”

To our knowledge, the telerobotic ultrasound clinics described in this paper 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 exams at a medical centre and seniors’ home 50 km away from the hospital at which the sonographer was based. In this series, telerobotic ultrasound exams were successful in 97% of cases.¹²⁴ The lower proportion of exams 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 exams were subjected to in our study. In another study, Arbeille et al. used motorized probes to scan the abdomen and pelvis, vascular structures, small parts (thyroid and muscle), and perform obstetrical exams. Images were deemed to be sufficient for diagnosis in 97% of cases in that series as well.⁶² 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.¹²⁷ 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 exams which are most suitable to be performed using a telerobotic ultrasound system. Diagnostic quality of abdominal, renal, first trimester obstetrical, and limited obstetrical telerobotic ultrasound exams was satisfactory in most cases; however, a large proportion of second trimester obstetrical ultrasound exams were recommended to be repeated. While recommending a follow-up exam to ensure all fetal anatomy is adequately assessed is common even when performing conventional ultrasound, the high number of exams 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.²³⁷ 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 exams were also limited as endovaginal scanning was not possible using the telerobotic ultrasound system.

The recent regulatory clearance of a telerobotic ultrasound system by the United States Food and Drug Administration and Health Canada^{52,107} 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 due to barriers in integrating one of the ultrasound machines into the province-wide PACS and RIS was resolved with involvement of key health system leaders in the remote community and at our academic medical centre. 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 set-up 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

exam 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 exams. 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 exams 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,^{5,54} 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.

7.6 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-degrees-of-freedom robotic arm and remotely performed ultrasound exams.
- Telerobotic ultrasound exams 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.

7.7 Acknowledgements

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CHAPTER 8

TELEROBOTIC ULTRASOUND TO REMOTELY PROVIDE OBSTETRICAL ULTRASOUND SERVICES DURING THE COVID-19 PANDEMIC*

The first case of COVID-19 in Saskatchewan was confirmed in March 2020. Following this initial case, case numbers rapidly increased and long-standing health inequities were underscored. Northern Saskatchewan communities were particularly vulnerable during the COVID-19 pandemic due to a multitude of social factors, such as suboptimal housing and overcrowding, as well as challenges in access to care. La Loche, a northern village in Saskatchewan, became the epicentre of the first wave of the COVID-19 pandemic in Saskatchewan. We rapidly developed a telerobotic ultrasound clinic to respond to the COVID-19 crisis in the community. Obstetrical ultrasound was prioritized by the community, and over a 5-week period during the COVID-19 outbreak in the community we performed 21 obstetrical ultrasound exams using the telerobotic ultrasound system. Chapter 8 presents results of using this technology to provide obstetrical ultrasound exams during the COVID-19 outbreak, demonstrating the potential of this technology to provide critical ultrasound services to an underserved northern population and help reduce health inequities during the COVID-19 pandemic.

* This chapter is based on:

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8.1 Abstract

Introduction: Obstetrical ultrasound imaging is critical in identifying at-risk pregnancies and informing clinical management. The COVID-19 pandemic has exacerbated challenges in accessing obstetrical ultrasound for patients in underserved rural and remote communities where this service is not available. This prospective descriptive study describes our experience of providing obstetrical ultrasound services remotely using a telerobotic ultrasound system in a northern Canadian community isolated due to a COVID-19 outbreak.

Methods: A telerobotic ultrasound system was used to remotely perform obstetrical ultrasound exams in La Loche, Canada, a remote community without regular access to obstetrical ultrasound. Using a telerobotic ultrasound system, a sonographer 605 km away remotely controlled an ultrasound probe and ultrasound settings. Twenty-one exams were performed in a 5-week period during a COVID-19 outbreak in the community, including limited first-, second-, and third-trimester exams (n = 11) and complete second-trimester exams (n = 10). Participants were invited to complete a survey at the end of the telerobotic ultrasound exam describing their experiences with telerobotic ultrasound. Radiologists subsequently interpreted all exams and determined the adequacy of the images for diagnosis.

Results: Of 11 limited obstetrical exams, radiologists indicated images were adequate in 9 (81%) cases, adequate with some reservations in 1 (9%) case, and inadequate in 1 (9%) case. Of 10 second-trimester complete obstetrical exams, radiologists indicated images were adequate in 2 (20%) cases, adequate with some reservations in 3 (30%) cases, and inadequate in 5 (50%) cases. Second-trimester complete obstetrical exams were limited due to a combination of body habitus, fetal lie, and telerobotic technology.

Conclusion: A telerobotic ultrasound system may be used to answer focused clinical questions such as fetal viability, dating, and fetal presentation in a timely manner while minimizing patient travel to larger centres and potential exposure to SARS-CoV-2 during the COVID-19 pandemic.

8.2 Introduction

The coronavirus disease 2019 (COVID-19) pandemic has exacerbated health inequities for many people around the globe.^{238–240} Challenges in accessing healthcare services, including diagnostic imaging services, have been exacerbated during the pandemic particularly in rural and

remote communities where limited availability of healthcare services forces patients to travel to larger centres for the care they need, increasing the risk of SARS-CoV-2 exposure and transmission. Lack of access to care has the potential to result in substantial negative outcomes, particularly among Indigenous populations with increased health disparities and increased susceptibility to COVID-19 due to multiple factors. Virtual care use has dramatically accelerated as a solution to promote physical distancing and ensure patients continue to receive the care they need, with up to a 10-fold increase in some regions.²⁴¹ However, virtual care has mostly consisted of telephone conversations or videoconferencing between patients and their physicians,²⁴² and remote solutions for diagnostic imaging are yet to be available in most communities.

Ultrasound imaging is a critical component of prenatal care to identify at-risk pregnancies and inform clinical management, including during the COVID-19 pandemic.²⁴³ The International Society of Ultrasound in Obstetrics and Gynecology recommends that first-trimester dating scans and second-trimester anatomical scans continue to be performed during the COVID-19 pandemic in asymptomatic patients and COVID-19 screen-negative patients.²⁴³ In Saskatchewan, Canada, first and second-trimester ultrasound exams are generally performed based on a schedule informed by the Society of Obstetricians and Gynaecologists of Canada's clinical practice guidelines. A first-trimester ultrasound is recommended to date a pregnancy (ideally at 7–12 weeks' gestation); alternatively, if menstrual dating is reliable, this can be deferred to the time of an early comprehensive pregnancy ultrasound performed at 11–14 weeks.¹³⁵ A routine second-trimester ultrasound is recommended between 18 and 22 weeks to screen for fetal anomalies, number of fetuses, gestational age, and the location of the placenta.¹³⁶ Additional obstetrical ultrasound exams are guided by the patient's clinical presentation, and current referral patterns include consultations for diagnostic ultrasound exams interpreted by radiologists to assess fetal viability, fetal presentation, amniotic fluid volume, and placenta location, among other indications. These ultrasound exams are universally available without billing directly to patients.

However, in Saskatchewan and in many communities around the world, sonographers, radiologists, and obstetricians are not available on a regular basis to perform obstetrical ultrasound exams. During the COVID-19 pandemic, travel to other communities for imaging has placed prenatal patients at increased risk of exposure to SARS-CoV-2 and subsequently transmitting the virus to the community to which they return. In other communities where

ultrasound exams are performed by an itinerant sonographer, their travel places the community to which they visit at increased risk, or places themselves and their home community at increased risk if traveling to an area with an outbreak. Solutions to provide local ultrasound services are urgently required in many communities around the world during the COVID-19 pandemic and beyond.

In this paper we describe our experience using a telerobotic ultrasound system—a robotic system which allows a sonographer to remotely perform a diagnostic ultrasound exam⁵⁴—to perform obstetrical ultrasound exams during a COVID-19 outbreak declared in La Loche, a northern village with a population of 2,372 people in Saskatchewan, Canada.^{244,245} Approximately 97% of the population of La Loche identifies as Indigenous,¹³⁹ and it is recognized that Indigenous women have a higher rate of obstetrical complications and two-fold greater maternal mortality rate than the general Canadian population.¹⁹³ Ultrasound services in this community are normally provided by a sonographer who travels to La Loche on a chartered flight one day each month, while patients who require urgent imaging are transported to a regional hospital 507 km away or a tertiary hospital approximately 595 km away. As La Loche experienced a COVID-19 outbreak in late April, the community was isolated and chartered flights for ultrasound were cancelled to minimize the spread of COVID-19 to other communities and ensure the safety of the sonographer and pilots who would be entering the community. We describe our experience providing telerobotic ultrasound services during the COVID-19 pandemic as a model for how health systems may wish to implement telerobotic ultrasound to improve access to diagnostic ultrasound imaging, increase patient safety, and reduce health inequities during the pandemic and beyond.

8.3 Methods

8.3.1 Image acquisition

This prospective descriptive study was approved by the University of Saskatchewan Biomedical Research Ethics Board (Bio 15-276).

Consecutive obstetrical patients scanned using a telerobotic ultrasound system at the La Loche Health Centre between April 30, 2020 and June 4, 2020 are described in this study. Participants were invited to have a telerobotic ultrasound exam and participate in the study if their physician or nurse practitioner requested an obstetrical ultrasound exam in La Loche.

Written informed consent was obtained from each participant to have a telerobotic ultrasound exam and to have their data included in a research study. No patients invited to participate in the study declined. Patients were scheduled for telerobotic ultrasound exams based on clinical urgency indicated on the requisition.

Prior to each telerobotic ultrasound exam, patients were screened for COVID-19 based on provincial health authority guidelines by an assistant at the La Loche Health Centre. One of two sonographers with 13 and 16 years' experience in ultrasound, respectively, remotely performed ultrasound exams using a telerobotic ultrasound system (MELODY system, Société AdEchoTech, Naveil, France). The MELODY system consists of (1) a three-degrees-of-freedom robotic arm (located at the patient-site) designed to manipulate an ultrasound probe, and (2) a fictive probe and electronic control box (located at the sonographer-site) which allows the sonographer to remotely control the scanning ultrasound probe (Figure 8.1).^{5,54} At the La Loche Health Centre, an ultrasound probe connected to a standard ultrasound unit (SonixTablet, Analogic, Peabody, Massachusetts) was attached to the robotic arm of the MELODY system. By manipulating a fictive probe, sonographers 605 km away from the patient at an ultrasound facility in Saskatoon, Saskatchewan, Canada, remotely controlled the ultrasound probe on the patient's body. All fine movements of the fictive probe, including rotation, rocking, and tilting, were replicated by the scanning probe in La Loche, though translation and pressure of the probe was controlled by an assistant in La Loche who held the frame for the robotic arm. The assistant was provided a one-hour training session on how to use the MELODY system prior to assisting with patient exams, though needed no prior experience with ultrasound.

The ultrasound unit interface was transmitted to a computer monitor at the ultrasound facility in Saskatoon via Tixeo Communication Client (Tixeo, Montpellier, France). This allowed the sonographer to view ultrasound images and remotely control ultrasound settings such as gain and depth. The radiologist supervising each exam could also view images acquired in real-time via Tixeo Communication Client. While this functionality was available for all exams and a radiologist was available if imaging findings needed to be clarified in real-time while the sonographer scanned the patient, it was left to the discretion of the radiologist whether they viewed the images as they were acquired in real-time or interpreted the exam based solely on the images archived in a picture archiving and communication system (PACS).



Figure 8.1. Telerobotic ultrasound system used during the COVID-19 pandemic. (A) At an ultrasound facility in Saskatoon, a sonographer manipulates a fictive ultrasound probe to control fine movements of the scanning ultrasound probe, including rotating, rocking, and tilting. The ultrasound unit interface is displayed for the sonographer to remotely view images generated in real-time and control all ultrasound unit settings. A videoconferencing monitor allows the sonographer to communicate with the patient and patient-site assistant. (B) At the La Loche Health Centre 605 km away from the sonographer, an assistant positions the frame for the robotic manipulator (MELODY system) over the patient's uterus. All movements the sonographer makes with the fictive probe are replicated by the ultrasound probe attached to the robotic manipulator.

A videoconferencing system (TE30 All-in-One, HD Videoconferencing Endpoint, Huawei Technologies, Shenzhen, China) was used to allow the sonographer, patient-site assistant, and patient to communicate with each other via Tixeo Communication Client.^{5,54}

The La Loche Health Centre and ultrasound facility in Saskatoon both had bandwidth capacity of 5 Mbps (symmetric), above the minimum requirement of 100 Kbps for robotic control data, 1 Mbps (symmetric) for video conferencing data, and 1.5 Mbps (symmetric) for ultrasound video data, as recommended by the vendor.

Sonographers performed all ultrasound exams as requested by the referring clinician based on routine imaging protocols.^{136,246} The duration of exams was determined from the time the first image was acquired to the time the last image was acquired. All images were archived in a PACS.

8.3.2 Assessment

After each telerobotic ultrasound exam, patients were invited to complete a survey form to provide comments regarding their experience with the telerobotic ultrasound exam and potential advantages or disadvantages of telerobotic ultrasound during the COVID-19 pandemic. Questions included, “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.”

Following each telerobotic ultrasound exam, sonographers also completed a data collection form indicating technical challenges experienced during the telerobotic ultrasound exam and contributing factors limiting exam quality, including increased body habitus, fetal lie, gestational age, and telerobotic technology.

Images were interpreted and reported by one of two board-certified radiologists based at Royal University Hospital in Saskatoon. The radiologists had six and 30 years’ experience, respectively, interpreting obstetrical ultrasound exams. Radiologists completed a standardized data collection form based on Adams et al.⁵⁴ after each study indicating the adequacy of the images for diagnosis and whether a repeat exam was recommended due to the diagnostic quality of the exam. Determination of the adequacy of images for diagnosis was based on the principle of whether, in routine clinical practice in an outpatient clinic setting, the radiologist would ask

the sonographer to acquire additional images or recommend further imaging. Diagnostic reports were generated and distributed to the referring clinician the same day or the day after each exam. The referring clinician subsequently discussed imaging findings with the patient as per routine clinical processes. In cases where images were not diagnostic, a follow-up ultrasound exam was recommended by the radiologist. The follow-up exam was provided either telerobotically or conventionally at the discretion of the referring clinician.

8.3.3 Statistical and qualitative analysis

Descriptive statistics, including frequencies and proportions for categorical variables and means and standard deviations for continuous variables, were determined. Free-text responses from patient surveys were analysed using thematic analysis.²³⁶ This involved familiarizing oneself with the data (free-text responses), generating initial codes, and searching, revising, and defining themes using an approach as described by Braun et al.²³⁶ Two team members reviewed the free-text responses to ensure that the themes effectively represented patient responses. Data was stored on a password-protected computer and all data was de-identified using an alternate identifier to maintain participant confidentiality.

8.4 Results

8.4.1 Patient demographics and exam indications

Twenty-one obstetrical telerobotic ultrasound exams were performed between April 30, 2020 and June 4, 2020. Three exams were follow-up studies for patients who previously had a telerobotic ultrasound exam during the study period, resulting in 18 unique patients scanned. Mean age (\pm standard deviation) of patients was 28.1 (\pm 6.2) years.

Five first-trimester exams, 10 second-trimester complete obstetrical exams, 2 second-trimester limited exams, and 4 third-trimester limited exams were performed. The mean duration of exams (standard deviation) was 11.4 (\pm 7.0) minutes for first-trimester studies, 38.1 (\pm 6.8) minutes for complete second-trimester exams, and 17.2 (\pm 8.7) minutes for limited second- and third-trimester exams. No adverse events related to telerobotic ultrasound exams were reported.

Indications for first-trimester exams were dating ($n = 3$), rule out ectopic pregnancy ($n = 1$), and query fetal demise ($n = 1$). Indications for second-trimester limited exams were to complete the anatomic assessment ($n = 1$) and complete the anatomic assessment and assess fetal position ($n = 1$). Indications for third-trimester exams were to assess fetal position ($n = 1$), assess

fetal position and growth ($n = 1$), no previous imaging ($n = 1$), and indication not specified ($n = 1$).

Initial telerobotic exams were repeated telerobotically for three patients: (1) a follow-up first trimester study to confirm fetal demise (in which the follow-up exam demonstrated a crown-rump length of 13 mm and absence of cardiac activity, confirming fetal demise; Figure 8.2), (2) a limited second-trimester study to assess fetal presentation, and (3) a second-trimester study to complete the anatomic assessment as some structures were suboptimally assessed on the initial exam.

8.4.2 Image assessment

For limited exams, radiologists indicated images were adequate in 9 of 11 (81%) cases, adequate with some reservations in 1 (9%) case, and inadequate in 1 (9%) case. For the first-trimester exam where images were inadequate, the sonographer indicated the exam was limited due to body habitus, a non-distended bladder, and the inability to perform endovaginal scanning.

For second-trimester complete obstetrical exams, radiologists indicated images were adequate in 2 of 10 (20%) cases, adequate with some reservations in 3 (30%) cases, and inadequate in 5 (50%) cases.

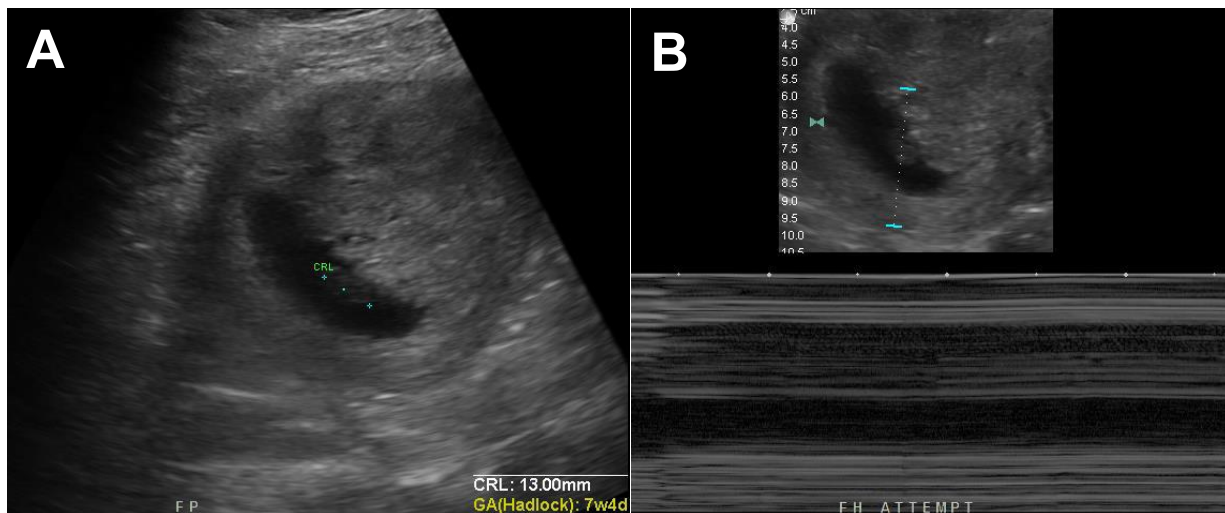


Figure 8.2. Gray scale and M-mode ultrasound images obtained using the telerobotic ultrasound system. (A) Ultrasound image generated using the telerobotic ultrasound system demonstrating an embryo with a crown-rump length of 13 mm. (B) No cardiac activity is demonstrated, confirming fetal demise.

Radiologists recommended that a follow-up study be performed for 2 (18%) limited studies and 7 (70%) second-trimester complete obstetrical studies. Of the 9 exams where a repeat study was recommended by the radiologist, 7 (77%) of these exams were limited due to fetal lie, 3 (33%) were limited due to body habitus, and 8 (88%) were limited due to telerobotic technological limitations (with most exams having multiple contributing factors leading to suboptimal diagnostic performance, as noted by the sonographer).

8.4.3 Technical challenges

Sonographers and the patient-site assistant reported that technical difficulties were experienced in 5 of 21 exams (24%) on four separate clinic days. In each of these cases there was a delay between the time the mock probe was repositioned and when the ultrasound interface displayed the new corresponding image. This included an intermittent delay in ultrasound video data with no significant impact on performance of the exam ($n = 2$) and significant delay of up to 5-10 s or freezing of the ultrasound video data requiring the system to be re-booted ($n = 3$). In two cases, minimal intermittent delay continued to be experienced following re-booting.

8.4.4 Patient assessment

Sixteen of 21 patients provided written comments on the survey form. Four themes were identified from patients' comments related to advantages of telerobotic ultrasound during the COVID-19 pandemic: (1) eliminating the need to travel, (2) increased ultrasound availability, including availability for emergencies and decreased wait times for exams, (3) convenience, and (4) safety, particularly prominent during the pandemic. Only one theme was identified related to disadvantages of telerobotic ultrasound during the COVID-19 pandemic: the ability to see images as they were being obtained, partially due to positioning of the ultrasound unit in relation to the patient.

8.5 Discussion

Obstetrical ultrasound imaging provides important information to guide clinical management by identifying at-risk pregnancies.²⁴³ However, the COVID-19 pandemic has increased maternal and fetal risk associated with obtaining obstetrical ultrasound due to potential exposure to SARS-CoV-2. This challenge is particularly great in geographically dispersed communities without regular access to ultrasound services as travel to a larger centre is required to obtain an ultrasound exam. Previous studies have compared conventional ultrasound to

telerobotic ultrasound to perform abdominal⁵ and obstetrical⁵⁴ ultrasound exams, as well as echocardiography,¹²³ generally finding excellent agreement between measurements between conventional and telerobotic scanning. In this paper we describe use of telerobotic ultrasound as a solution for patients in underserved rural and remote communities to receive obstetrical ultrasound exams in a way that minimizes travel during the COVID-19 pandemic.

Creative solutions are being explored across healthcare systems to minimize exposure to SARS-CoV-2 while meeting obstetrical care needs during the COVID-19 pandemic. The International Federation of Gynecology and Obstetrics (FIGO) has recommended that in-person clinic visits in low-risk patients with uncomplicated pregnancies be decreased and replaced by phone calls or videoconferencing,²⁴⁷ and across specialities, there has been a dramatic increase in virtual care.^{242,248,249} However, the provision of ultrasound services is an aspect that is not served through traditional virtual care tools.²⁴⁷ Baylor College of Medicine developed a drive-through prenatal care program, which includes limited ultrasound exams performed from the patient's vehicle, to reduce the number of in-person clinic visits during the COVID-19 pandemic.²⁵⁰ While this may be a promising approach in urban centres, rural and remote communities without regular access to obstetrical ultrasound exams experience unique challenges, and it is incumbent upon providers to ensure provision of diagnostic ultrasound services in a way that protects patients and healthcare providers and minimizes expenditure of healthcare resources during the pandemic.

Patients in our study appreciated the benefits of telerobotic ultrasound as minimizing the need for travel and ensuring safety, particularly important during the COVID-19 pandemic. While identifying at-risk pregnancies and providing other non-COVID-19 care continues to be of importance during the pandemic,²⁴³ it has also been suggested that ultrasound exams may serve as reassurance to patients and their families, which helps reduce stress and anxiety for patients and their partners during the pandemic.²⁴³ Obstetrical ultrasound may also help promote parental bonding with the developing fetus.²⁵¹ As patients may otherwise travel for ultrasound imaging to a larger city alone (particularly during the COVID-19 pandemic), at a substantial distance from their home community, telerobotic ultrasound allows patients to be near their family to share their ultrasound results and have family readily available for support in the case of negative outcomes such as fetal demise.

The benefits of telerobotic ultrasound to locally provide ultrasound services may be particularly great in Indigenous communities in Canada due to the higher rate of obstetrical complications among Indigenous peoples. A study in Quebec, Canada found a rate of stillbirths of 5.7 per 1000 and 6.8 per 1000 births among First Nations and Inuit peoples, respectively, compared to 3.6 per 1000 among non-Indigenous residents.²⁰ Another study in Manitoba, Canada, found a rate of stillbirth of 8.9 per 1000 among First Nations residents compared to 5.3 per 1000 among non-First Nations residents ($p < 0.01$).²¹ Higher rates of stillbirths and neonatal mortality among Indigenous populations may be due to multiple related factors, such as post-colonial policies, socioeconomic status, housing, diet, tobacco and alcohol use, other environmental exposures, and accessibility to healthcare services.¹⁹³ These may translate to poor fetal growth, placental disorders, congenital anomalies, and diabetic and hypertensive complications, which have been shown to be strongly associated with stillbirth in First Nations and Inuit populations.²⁰ Ultrasound is particularly well-suited to identify resulting obstetrical complications, such as disturbances in fetal growth, amniotic fluid abnormalities, or fetal anemia.²⁵² In addition to an increased rate of obstetrical complications in Indigenous populations, the arduous travel and cultural challenges experienced by many Indigenous women and families suggests that telerobotic ultrasound technology may have an important role in ensuring equitable access to ultrasound services.

Despite the many benefits of locally-provided telerobotic ultrasound, some limitations to providing local ultrasound exams using telerobotic ultrasound systems should be acknowledged. A number of structures which are part of a second-trimester complete obstetrical exam were suboptimally visualized on telerobotic exams due to difficulties in manipulating the probe into the correct plane using the telerobotic ultrasound system, and a repeat exam was recommended for a high proportion of complete second-trimester exams. This is consistent with our prior work, which has suggested that the fetal cavum septi pellucidi, cardiac outflow tracts, spine, and kidneys are most difficult to be visualized using the telerobotic ultrasound system.⁵⁴ Latency in ultrasound video may further contribute to difficulties in adequately assessing all required anatomy in a timely manner, and clinics must ensure sufficient bandwidth for telerobotic exams. While our results suggest that first-trimester and focused second- and third-trimester ultrasound exams can be effectively performed using a telerobotic ultrasound system, second-trimester complete ultrasound exams may best be performed through conventional (non-telerobotic)

scanning. However, challenges in visualizing all fetal anatomy are also common with conventional scanning, especially in obese individuals. Completion rates of a comprehensive anatomic survey are as low as 43% in normal weight individuals and 31% in class III obese individuals, with a mean number of scans needed to complete a comprehensive anatomic survey of 1.7 for normal weight individuals and 2.2 for class III obese individuals.²³⁷

One of the disadvantages of telerobotic ultrasound as demonstrated in previous studies is variably longer exam times as compared to conventional scanning,⁵ which is of particular concern during the COVID-19 pandemic as the amount of time assistants are in the same room as patients should be minimized.²⁵³ Some authors have suggested that abbreviated ultrasound protocols can be used during the pandemic to reduce the time that the sonographer is in contact with patients.²⁵³ A similar justification could be used for telerobotic ultrasound to minimize contact between patients and assistants. Another strategy to further reduce exam times is capturing specific planes and completing measurements offline.^{243,253}

There are several considerations to ensure patient and provider safety during telerobotic ultrasound exams during the COVID-19 pandemic. Although telerobotic ultrasound minimizes potential exposure to SARS-CoV-2 among sonographers remotely performing exams, screening patients before each telerobotic ultrasound exam as per institutional protocol remains critical to ensure safety of the assistants at the patient-site and other patients who may contact possible COVID-19 positive patients in common areas. Institutional guidelines and guidelines from professional societies regarding patient screening prior to ultrasound exams, including temperature checks, history regarding travel, occupation, contacts, and clusters, and inquiry regarding clinical symptoms,^{243,253} should be considered when implementing a telerobotic ultrasound service. Appropriate personal protective equipment should be worn by patient-site assistants as per institutional protocol, and consideration can be given to asking patients to wear surgical masks during exams.²⁵⁴ Similar to requirements for conventional ultrasound during the COVID-19 pandemic, the ultrasound transducer and telerobotic ultrasound unit should be cleaned with a compatible low-level disinfectant after each patient, with additional requirements following suspected or confirmed COVID-19 cases.²⁵⁵

While in this paper we demonstrate the potential for telerobotic ultrasound to facilitate non-COVID-19 related care during the pandemic, telerobotic ultrasound may also be used in inpatient or outpatient settings for patients with or suspected to have COVID-19. Institutions

have reported significantly increased ultrasound exam times for COVID-19 positive patients due to infection control precautions (for example, 90 minutes for a bilateral lower extremity Doppler ultrasound study to rule out deep vein thrombosis rather than the usual 30 minutes).²⁵³ The use of telerobotic ultrasound would eliminate the need for sonographers to don and doff personal protective equipment to perform ultrasound exams and minimize the use of personal protective equipment by having healthcare workers already working on the COVID-19 unit assist with exams. Further, the use of telerobotic ultrasound may minimize sonographers' potential exposure to COVID-19 and minimize possible disruptions to ultrasound operations should the sonographers need to self-isolate, particularly important considering the limited number of sonographers available in most health systems. While exam time may be longer using telerobotic ultrasound technology compared to conventional scanning, overall process time may be reduced if sonographers are not required to travel to the patient's bedside and don and doff personal protective equipment, improving radiology throughput.

There are some study limitations. First, only telerobotic ultrasound exams were performed for each patient as part of this study, with no comparison to conventional ultrasound as a reference standard to assess diagnostic accuracy or provide data on the proportion of exams for which follow-up would be recommended had the exams been performed conventionally. The lack of availability of ultrasound services in La Roche and the need to minimize patient and healthcare provider contact during a COVID-19 outbreak in the community made it impractical to compare all telerobotic exams to conventional exams. Second, only a single reader interpreted each study and concordance between each radiologist's assessment regarding the diagnostic quality of each study was not assessed. This limitation is mitigated by the significant experience each radiologist has in reading obstetrical ultrasound studies, providing confidence in the interpretations provided. Further, the small sample size and that all telerobotic ultrasound exams were performed at a single site limit generalizability of the study.

8.6 Conclusion

This study demonstrates the feasibility of telerobotic ultrasound as a means to provide obstetrical ultrasound exams during the COVID-19 pandemic in a community which would not otherwise have had locally available services due to a COVID-19 outbreak. Exams successfully answered clinical questions regarding fetal viability, dating, and fetal presentation in a timely

manner, though assessment of anatomy in second-trimester exams was limited due to multiple factors. Our experience provides a model for how telerobotic ultrasound may improve access to diagnostic ultrasound imaging, increase patient safety, and reduce health inequities during the COVID-19 pandemic. This technology may be particularly important in Indigenous communities with increased pregnancy rates, increased rates of obstetrical complications, and cultural and logistical challenges related to access to care. It is likely that the COVID-19 pandemic will further catalyze the implementation of virtual care solutions such as telerobotic ultrasound to bring greater accessibility of health care services, including diagnostic ultrasound, to patients. Future studies are required to determine the sustainability and clinical and economic implications of performing telerobotic ultrasound exams beyond the current COVID-19 pandemic.

8.7 Acknowledgements

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CHAPTER 9

ECONOMIC EVALUATION OF TELEROBOTIC ULTRASOUND TECHNOLOGY TO REMOTELY PROVIDE ULTRASOUND SERVICES IN NORTHERN, REMOTE COMMUNITIES*

Chapters 7 and 8 demonstrated the feasibility of a telerobotic ultrasound clinic model to remotely provide ultrasound services in northern, remote communities and thereby improve access to ultrasound imaging. Using telerobotic ultrasound, most patients were able to stay in their home community for an ultrasound exam, providing timely access to ultrasound imaging and minimizing patient travel. The economic sustainability of using telerobotic ultrasound to provide ultrasound services in northern, remote communities is an important consideration to inform health system implementation. Chapter 9 presents an economic evaluation of an ultrasound service delivery model incorporating telerobotic ultrasound, comparing costs associated with telerobotic ultrasound to alternate models, including having an itinerant sonographer provide most ultrasound exams and requiring patients to travel for all ultrasound exams. Results from this study provide important information for health system decision makers considering ultrasound service delivery options in northern, remote communities.

* A manuscript based on this chapter is currently under review with a peer-reviewed journal as: Adams SJ, Penz E, Imeah B, Burbridge B, Obaid H, Babyn P, Mendez I. Economic evaluation of telerobotic ultrasound technology to remotely provide ultrasound services in rural and remote communities.

9.1 Abstract

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 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 option 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.

9.2 Introduction

The provision of healthcare services 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.²⁴⁻²⁶ The provision of ultrasound imaging services is particularly challenging in these communities as radiologists and sonographers with specific expertise are

required.¹ 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.¹⁷¹ Depending on the proximity to ultrasound facilities, traveling for an ultrasound exam sometimes requires an overnight stay, resulting in isolation from family and financial challenges when travelling to a city for imaging. In other communities where an itinerant sonographer visits the community on a monthly basis, long wait times often result.¹⁷¹

Telerobotic ultrasound is a new technology which equips a sonographer or radiologist with the ability to remotely manipulate an ultrasound probe, control all ultrasound settings, and, in this way, remotely perform an ultrasound exam (Figure 9.1).¹⁶⁷ Clinical trials which have demonstrated the feasibility of a telerobotic approach for performing abdominal and obstetrical ultrasound imaging^{5,54} and recent commercialization of telerobotic ultrasound systems^{51,53,109} have paved the way for implementation of this technology in rural and remote communities which do not have sonographers or radiologists on-site to perform ultrasound exams. Our group recently 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.¹⁶⁸ Using this technology, patients were able to have some ultrasound exams in their home communities, providing timely access to ultrasound imaging and minimizing patient travel. Most telerobotic ultrasound exams adequately answered clinical questions, though some limitations of telerobotic ultrasound were identified, including intermittent delay in transmission of images and difficulty assessing some anatomy due to patient body habitus, gestational age, and telerobotic technology.

To inform the implementation of telerobotic ultrasound technology in health systems, it is critical to explore its cost impact compared to other models of providing ultrasound services to a population dispersed within many small communities over a large geographic area. Lofgren et al. conducted a cost analysis in Sweden comparing the remote provision of echocardiography using a telerobotic ultrasound system to a model where patients had to travel to a larger centre for imaging.¹²⁸ They found that the telerobotic ultrasound model cost slightly more per ultrasound exam from the health system's perspective (county's perspective), though patient costs were substantially reduced using the telerobotic ultrasound service delivery model.¹²⁸ No evidence currently exists regarding the cost-effectiveness of telerobotic ultrasound for general diagnostic ultrasound, including abdominal, pelvic, and obstetrical exams. To address this knowledge gap,



Figure 9.1. 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 sonographer or radiologist can control all ultrasound settings required to remotely perform an ultrasound exam. (Images used with permission of AdEchoTech.)

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.

9.3 Methods

9.3.1 Study design, time horizon, and perspective

Based on prior clinical studies,^{5,54} equivalent diagnostic performance between telerobotic and conventional methods was assumed among ultrasound exams for which the radiologist does not recommend that the exam be repeated conventionally due to inadequate assessment of all anatomy. 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.^{128,256,257} 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.²⁵⁸

9.3.2 Setting and base case population

The base case assumed implementation of telerobotic ultrasound in a community representative of La Loche, a northern village in Saskatchewan, Canada, and the nearby Clearwater River Dene Nation, which is also served by the La Loche Health Centre. Our base case assumed a community population of approximately 3,200 people.^{244,259} Using La Loche as the model community, the closest ultrasound facility with daily on-site ultrasound services was determined to be Prince Albert, Saskatchewan, Canada, 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 from January 1, 2014 to December 31, 2018 (capturing all diagnostic ultrasound exams billed in private facilities over this time period) and exams included in the provincial Radiology Information System from January 1, 2014 to December 31, 2018 (capturing all

diagnostic ultrasound exams performed in public facilities). Ultrasound-guided procedures and subspecialized exams, including echocardiography and musculoskeletal ultrasound, were excluded from the analysis.

9.3.3 Ultrasound service delivery models

Four service delivery models for the provision of ultrasound services in rural and remote communities were compared (Table 9.1).

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 per day, seven days per week and that the telerobotic ultrasound clinics had sufficient capacity to meet demand in the community.

Table 9.1. Ultrasound service delivery models for rural and remote communities

Model	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

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. 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.^{5,54} 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 are not performed using the telerobotic ultrasound system and any patients requiring a second trimester complete obstetrical exam are referred for a conventional exam in another community. We also assumed that any ultrasound exams that are recommended to be repeated conventionally following a telerobotic ultrasound exam are performed conventionally in another community to which the patient must travel.

We assumed that a non-dedicated receptionist is required at the patient-site to assist with patient registration for telerobotic ultrasound exams, requiring approximately 5 minutes per patient. An assistant is required to assist with ultrasound exams at the patient-site for the duration of exams. We assume that telerobotic exams are scheduled in 1 hour increments and that the time commitment of the patient-site assistant is approximately 1 hour per exam.

Model 2 similarly represents the deployment of a telerobotic ultrasound system in a remote community; however, any ultrasound exams that cannot be performed using the telerobotic ultrasound system (including second trimester complete obstetrical exams) are performed by an itinerant sonographer who travels to the community to perform ultrasound exams at a frequency necessary to meet ongoing demand. We assumed that the sonographer travels to the community by air transportation (if traveling at least 350 km) or road transportation (if traveling less than 350 km) and performs an average of 12 ultrasound exams, without staying overnight in the remote community.²⁶⁰

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.²⁶¹ 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.²⁶¹

Model 4 assumes that no ultrasound services are locally available, neither through telerobotic ultrasound clinics nor an itinerant sonographer, and that all patients requiring an ultrasound exam must travel to another community.

9.3.4 Cost inputs

Cost estimates related to the performance of ultrasound exams in each of the four models are presented in Table 9.2. 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).²⁵⁸ All costs were expressed in 2020 Canadian dollars.

Fixed costs for telerobotic ultrasound exams. The cost of the telerobotic ultrasound unit included costs for the patient-site and sonographer-site components of the robotic arm of the telerobotic ultrasound system, ultrasound machine, and videoconferencing system (estimated from actual costs of the MELODY system, AdEchoTech, France). Capital costs for the ultrasound machine were annualized using a life expectancy of nine years based on the Canadian Association of Radiologists' expected life expectancy for ultrasound equipment of 9 years for a low utilization rate,²⁶² and capital costs for the telerobotic ultrasound system and videoconferencing system were annualized over a life expectancy of 12 years based on a vendor estimate. Annual maintenance costs for all capital equipment was set at 10% of the purchase price, consistent with current industry practice and prior literature.²⁵⁶ Training for sonographers and patient-site assistants was assumed to be 1 hour in duration,¹⁶⁸ and these costs were annualized over 3 years to account for staff turnover at a similar interval. As the telerobotic ultrasound system can share unused multi-purpose space (e.g. sharing space in a room for electrocardiography or bloodwork based on experience deploying telerobotic ultrasound systems in Saskatchewan communities), no costs were allocated for space at the patient-site.

Variable costs for telerobotic ultrasound exams. Although no fee is currently available for the technical component of telerobotic ultrasound exams, for the purposes of this study a total cost of \$60 per hour for sonographer salary, benefits, workspace, and internet provider costs was assumed. Fees for radiologists to interpret telerobotic ultrasound exams were based on the interpretation component for each respective type of ultrasound exam as listed in the October

Table 9.2. 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])				
<i>Fixed costs</i>				
Telerobotic ultrasound system (patient-site and sonographer-site)*	\$ 154,000.00	\$ 14,118.72		Personal communication (AdEchoTech)
Ultrasound machine*	\$ 54,000.00	\$ 6,458.93		Personal communication (AdEchoTech)
Videoconferencing systems (patient-site and sonographer-site)*	\$ 15,000.00	\$ 1,794.15		Personal communication (AdEchoTech)
Annual maintenance for all capital equipment (10% purchase price)*		\$ 22,300.00		Halvorsen and Kristiansen ²⁵⁶ and personal communication (AdEchoTech)
Shipping of equipment to remote community*	\$ 170.00	\$ 20.33		Personal communication (Department of Surgery, University of Saskatchewan)
Patient-site assistant training (2 patient-site assistants x 1 hour each at \$23.50/hour and 1 trainer x 2 hours at \$45/hour; assuming staff turnover every 3 years)*	\$ 137.00	\$ 47.04		Personal communication (Department of Surgery, University of Saskatchewan)
Sonographer training (2 sonographers x 1 hour each at \$60/hour and 1 trainer x 2 hours at \$45/hour; assuming staff turnover every 3 years)*	\$ 210.00	\$ 72.11		Personal communication (Department of Surgery, University of Saskatchewan and Ultrasound Centre, Saskatoon)
<i>Variable costs</i>				
Sonographer salary and benefits (1 hour for each exam at \$60/hour)*			\$ 60.00	Personal communication (Ultrasound Centre, Saskatoon)

Patient-site assistant salary and benefits (1 hour for each exam at \$23.50/hour)*	\$	23.50	Personal communication (Northern Medical Services)
Receptionist salary and benefits (5 minutes for each exam at \$23.50/hour)*	\$	1.96	Personal communication (Northern Medical Services)
Radiologist interpretation fee (weighted average of non-obstetrical ultrasound exams)	\$	43.17	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan</i> ²¹⁶
Radiologist interpretation fee (weighted average of obstetrical ultrasound exams excluding second trimester complete exams)	\$	44.06	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan</i> ²¹⁶
Radiologist interpretation fee (second trimester obstetrical ultrasound exams)	\$	51.25	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan</i> ²¹⁶

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*	\$	54,000.00	\$	6,458.93	Personal communication (AdEchoTech)
Annual maintenance (10% purchase price)*			\$	5,400.00	Halvorsen and Kristiansen ²⁵⁶
Shipping*	\$	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)*	\$	54.17	Personal communication (Northern Medical Services)
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Receptionist salary and benefits (5 minutes per exam at \$23.50/hour)*	\$ 1.96	Personal communication (Northern Medical Services)
Radiologist interpretation fee (weighted average of non-obstetrical ultrasound exams)	\$ 43.17	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan</i> ²¹⁶
Radiologist interpretation fee (weighted average of obstetrical ultrasound exams excluding second trimester complete exams)	\$ 44.06	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan</i> ²¹⁶
Radiologist interpretation fee (second trimester complete ultrasound exams)	\$ 51.25	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan</i> ²¹⁶
Sonographer air travel to community ≥ 350 km away (\$7,000 round trip charter flight shared among an average of 2.7 passengers, with an average of 12 ultrasound exams performed per trip, round-trip)*	\$ 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)*	\$ 14.29	Canada Revenue Agency ²⁶³

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*²¹⁶

Variable costs

Technical and interpretation fee (weighted average of non-obstetrical ultrasound exams)	\$ 119.10	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan²¹⁶</i>
Technical and interpretation fee (weighted average of obstetrical ultrasound exams excluding second trimester complete exams)	\$ 119.05	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan²¹⁶</i>
Technical and interpretation fee (second trimester complete ultrasound exams)	\$ 138.40	<i>Payment Schedule for Insured services Provided by a Physician for Saskatchewan²¹⁶</i>
Medical transportation costs (to ultrasound facility between 0-350 km from home community, round-trip)†	\$ 243.64	Personal communication (Indigenous Services Canada)
Medical transportation costs (to ultrasound facility between 350-700 km from home community, round-trip)*†	\$ 609.62	Personal communication (Indigenous Services Canada)
Medical transportation costs (to ultrasound facility >700 km from home community, round-trip)†	\$ 2,834.00	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)*	\$ 490.00	Canada Revenue Agency ²⁶³
Air travel (round trip)*	\$ 855.00	Transwest Air ²⁶⁴
Accommodation (1 night at \$103.67/night)*	\$ 103.67	CBRE Hotel Industry Statistics for Saskatchewan via Ontario Ministry of Tourism, Culture and Sport ²⁶⁵
Meals (2 days at \$69/day)*	\$ 138.00	Canada Revenue Agency ²⁶³

Lost income (0.5 days based on average income of \$36,475)‡	\$ 49.97	Statistics Canada ^{244,259}
Lost income (2 days based on average income of \$36,475)‡	\$ 199.87	Statistics Canada ^{244,259}
Child care (\$41/day/child; assuming 0.5 days of child care are required)*	\$ 20.50	Canadian Centre for Policy Alternatives ²⁶⁶
Child care (\$41/day/child; assuming 2 days of child care are required)*	\$ 82.00	Canadian Centre for Policy Alternatives ²⁶⁶

* All costs indicated with an asterisk were varied based on a gamma distribution in the reference case multi-way probabilistic analysis.²⁶⁷

† Medical transportation costs included transportation, hotel accommodations, and meal vouchers, when available.

‡ 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 multi-way probabilistic analysis

2020 *Payment Schedule for Insured services Provided by a Physician* for Saskatchewan.²¹⁶ A weighted average of interpretation fees for obstetrical and non-obstetrical ultrasound exams was determined based on the frequency of each exam type from analysis of Saskatchewan Ministry of Health physician billing data from 2014 to 2018. Salaries for the patient-site assistant (with a time commitment of 1 hour per exam) and patient-site receptionist (5 minutes per exam) are listed in Table 9.2.

Fixed costs for ultrasound exams performed by an itinerant sonographer. Conventional exams performed in a remote community were assumed to use an ultrasound machine similar to that used for telerobotic ultrasound exams. Annual maintenance costs for the ultrasound unit were set at 10% of the purchase price.²⁵⁶

Variable costs for ultrasound exams performed by an itinerant sonographer. Transportation costs for the itinerant sonographer were based on charter flight costs from the closest city to the model community, divided by the number of ultrasound exams performed each day by the sonographer and the average number of passengers on the charter flight. Cost estimates were obtained from Northern Medical Services of the University of Saskatchewan, the unit currently responsible for the provision of medical services for the northern Saskatchewan population, which charts flights to allow physicians and sonographers to travel to northern communities on an itinerant basis. Sonographers were assumed to receive a flat rate of \$650 per day for their professional service based on personal communication with Northern Medical Services. Costs for ultrasound exam interpretation were based on the Saskatchewan physician payment schedule.²¹⁶ Receptionist costs were estimated to be identical to that required for telerobotic ultrasound exams. As for telerobotic ultrasound exams, it was assumed that ultrasound exams were performed in unused multi-purpose space and thus no costs were allocated for space at the patient-site.

Ultrasound exams performed in a community to which the patient had to travel. Technical and professional components for ultrasound exams performed in community clinics were obtained from the October 2020 *Payment Schedule for Insured services Provided by a Physician*.²¹⁶ The technical component is intended to cover all aspects related to performance of an ultrasound exam, such as ultrasound equipment, facility, and salary costs, and thus all costs are represented as variable costs.

Travel costs. As travel costs are generally covered through federal or First Nations funding for First Nations people registered under the *Indian Act* (status Indians) but are borne directly by individuals who are not status First Nations,²⁶⁸ travel costs were allocated to the publicly funded healthcare payer for 59% of the population in the model community, consistent with population demographics of the model community in which 59% of community members identify as First Nations (in our analysis, used as an estimate for the proportion of the population eligible for publicly funded medical transportation).²⁴⁴ Travel costs for individuals eligible for publicly funded medical transportation were based on average costs for medical transport to and from communities within Census Division No. 18 (northern Saskatchewan, Canada) as obtained from Indigenous Services Canada's Medical Transportation Records System. Travel authorization amounts related to an obstetrical or non-obstetrical ultrasound in the 2017, 2018, and 2019 calendar years were stratified by travel distance <350 km, 350-700 km, and >700 km, and subsequently averaged. Travel costs included transportation costs, hotel accommodations, and meal vouchers, when available.

Additional costs from a societal perspective. Additional costs considered in the non-reference case analysis from a societal perspective included transportation, accommodation, and meal costs borne by patients; productivity costs for lost time away from paid work; and child care costs. Transportation costs for those whose medical transportation costs are not publicly funded (which are borne directly by patients, and thus were considered in the analysis from a societal perspective only) were determined by multiplying the distance to the nearest ultrasound facility by the Government of Canada's 2020 automobile allowance rate for Saskatchewan (\$0.49 per km),²⁶³ similar to methodology previously employed in the literature.²⁶⁹ Transportation was assumed to be by air for communities 750 km or greater from the closest ultrasound facility. In this case, transportation costs were determined based on published airfares from a commercial airline.²⁶⁴ One night's accommodation was assumed to be required if traveling at least 500 km to an ultrasound facility. Meal costs were estimated based on Government of Canada 2020 meal rates.²⁶³

A human capital approach was used to value lost time away from paid work and these costs were included in the non-reference case analysis from a societal perspective.²⁵⁸ We assumed that an ultrasound exam provided locally (telerobotically or by the itinerant sonographer) would result in 0.5 days off work, while an ultrasound in another community to

which a patient had to travel would result in 2 days off work. Productivity costs were based on average after-tax income of \$36,475 (adjusted from 2015 values using the Consumer Price Index) among the 28% of the total population who received income from employment.^{244,259} Consistent with current recommendations, lost leisure time was not included as a cost.²⁵⁸ Child care costs were estimated based on the average of median child care fees for Saskatchewan²⁶⁶ with an estimated proportion of 32% of patients with children 14 years or younger requiring child care.²⁷⁰

9.3.5 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 multi-way probabilistic analyses (Table 9.3). 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, a one-way sensitivity analysis was conducted to determine differences in average cost per ultrasound exam as population size of the model community varied from 250 people to 10,000 people (with corresponding changes in the volume of ultrasound exams required in the community) with all other model parameters and cost estimates held constant. One-way sensitivity analyses were also conducted to determine differences in average cost per ultrasound exam as distance to the nearest facility with regular ultrasound services varied between <350 km, 350-700 km, and >700 km, and as the proportion of the population eligible for publicly funded medical transportation varied. Additionally, a one-way sensitivity analysis was conducted as the proportion of telerobotic exams which were recommended to be performed conventionally due to limited assessment of some anatomic structures varied. Finally, a one-way sensitivity analysis was conducted as the frequency of itinerant sonographer visits varied. Similar to the base case analysis, it was assumed that the itinerant sonographer could perform an average of 12 ultrasound exams per trip,²⁶⁰ and it was assumed that patients would have to travel to another community for any ultrasound exams beyond the capacity of the itinerant sonographer at the given frequency of visits.

Table 9.3. Model parameters

Parameter	Base case value	Sensitivity analysis	Reference
Population and community characteristics			
Population size	3,200	Varied from 250-10,000 in a one-way sensitivity analysis. Held constant in the reference case multi-way probabilistic analysis.	Statistics Canada ^{244,259}
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 0-100% in a one-way sensitivity analysis. Varied using a Bernoulli distribution in the reference case multi-way probabilistic analysis.	Statistics Canada ^{244,259}
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 ²⁷⁰
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	Chapter 5
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	Chapter 4

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	Chapter 4
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	Chapter 7
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	Chapter 7
Itinerant sonographer			
Ultrasound exams performed per day	12	Varied using a Poisson distribution in the reference case multi-way probabilistic analysis	Northern Medical Services ²⁶⁰
Number of people traveling on the charter flight	2.7	Varied from 1-4 persons using a uniform distribution in the reference case multi-way probabilistic analysis	Personal communication (Northern Medical Services)
Ultrasound priority			
Proportion of non-obstetrical ultrasound exams which are Priority 1 or 2	20%	Varied from 10-30% using a uniform distribution in the reference case multi-way 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 10-30% using a uniform distribution in the reference case multi-way probabilistic analysis	Personal communication (University of Saskatchewan Department of Surgery/Northern Medical Services)
Discount rate			
Discount rate	1.5%	Varied from 0-3% using a uniform distribution	CADTH ²⁵⁸

Note: Costs presented in Table 9.2 were varied using a gamma distribution. Parameters α and β were determined using the method of moments approach.²⁶⁷ 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.²⁷¹

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

9.4 Results

9.4.1 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, including 95% confidence intervals, are presented in Table 9.4.

Table 9.4. 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)

CI, confidence interval.

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 9.2A). For communities with less than 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 9.3A). 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 less than 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 9.4A). For communities with between 28% and 47% of the population eligible for publicly funded medical transportation, Model 1 (telerobotic ultrasound) was the lowest cost, and for communities with greater than or equal to 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 less than 8% (Figure 9.5A). 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 greater than 37%.

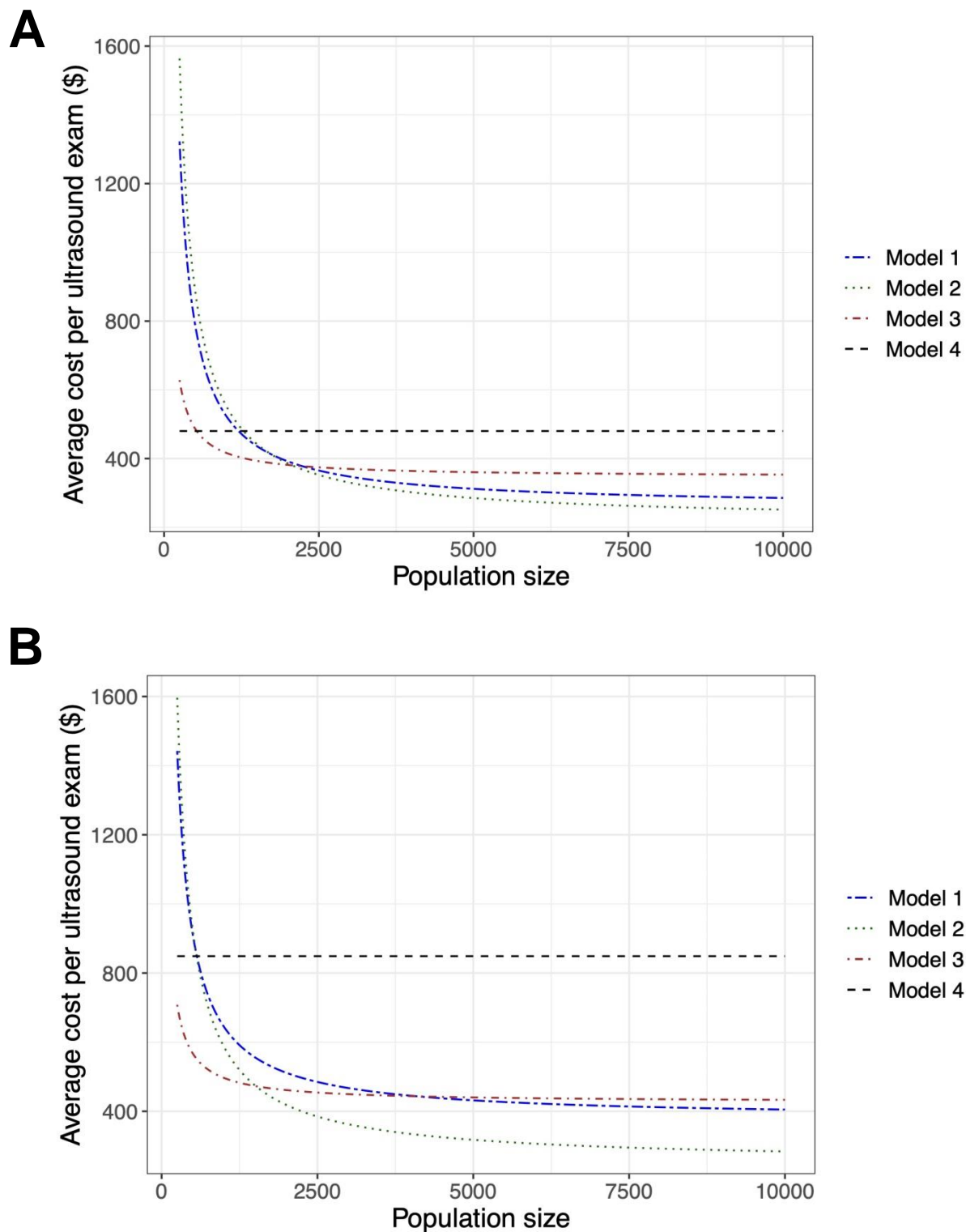


Figure 9.2. Average cost per ultrasound exam for each ultrasound service delivery model from a (A) publicly funded healthcare payer perspective and (B) societal perspective as community population size varies. All other parameters are held constant in each model.

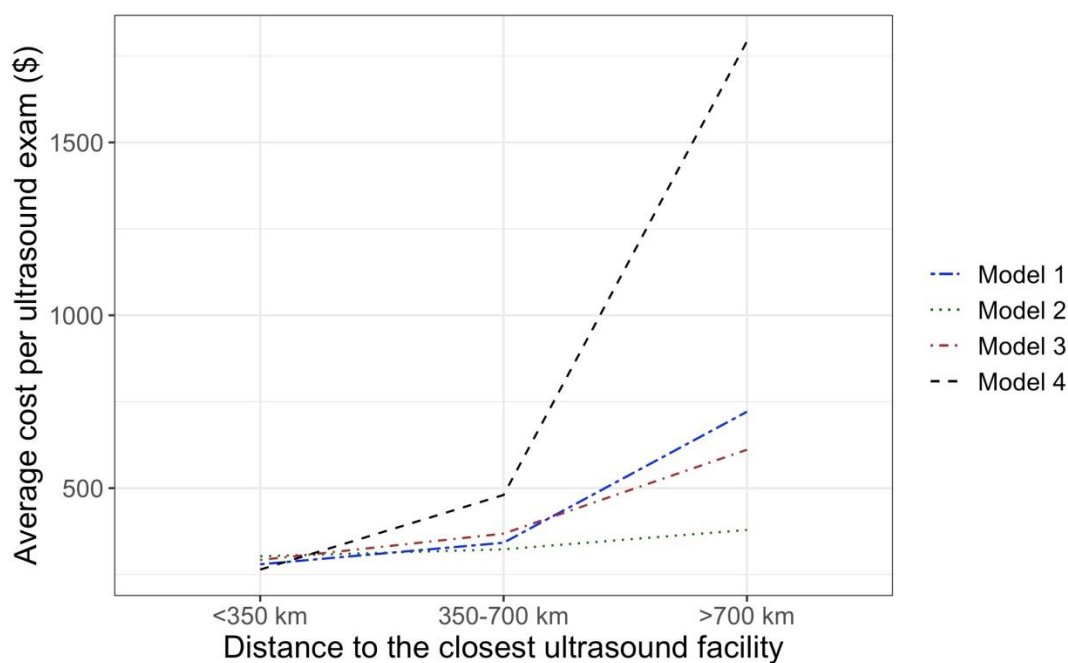
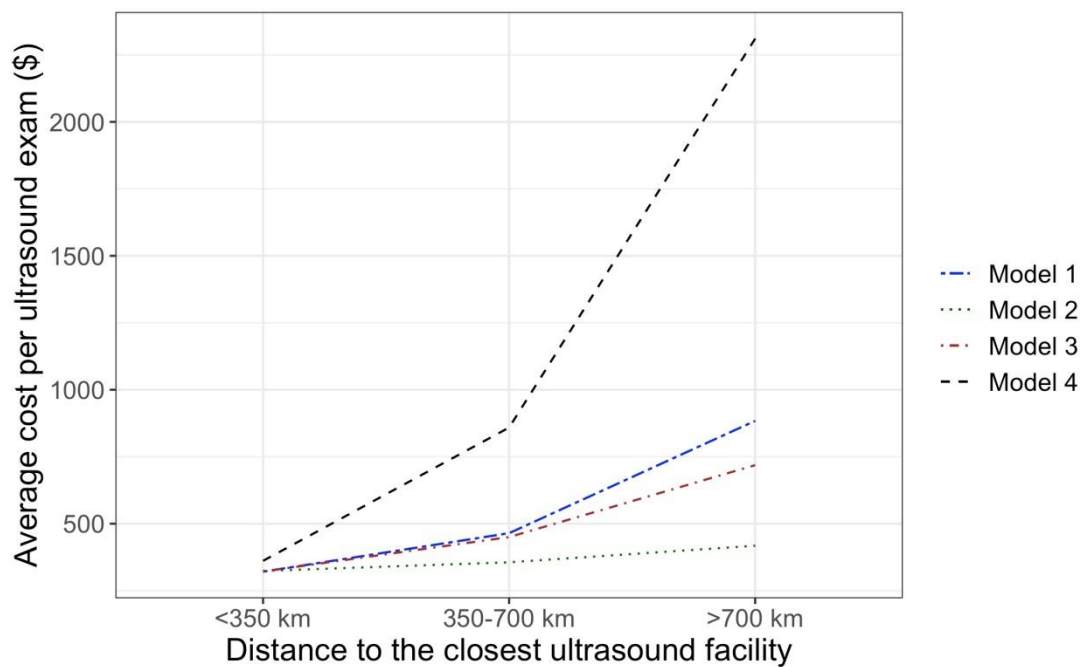
A**B**

Figure 9.3. 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.

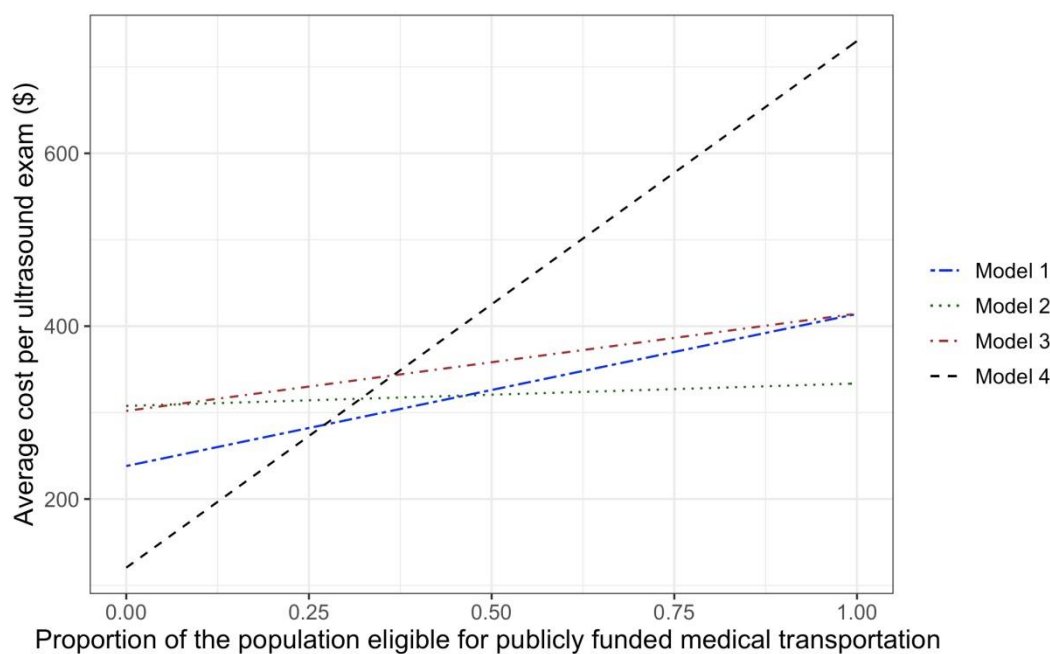
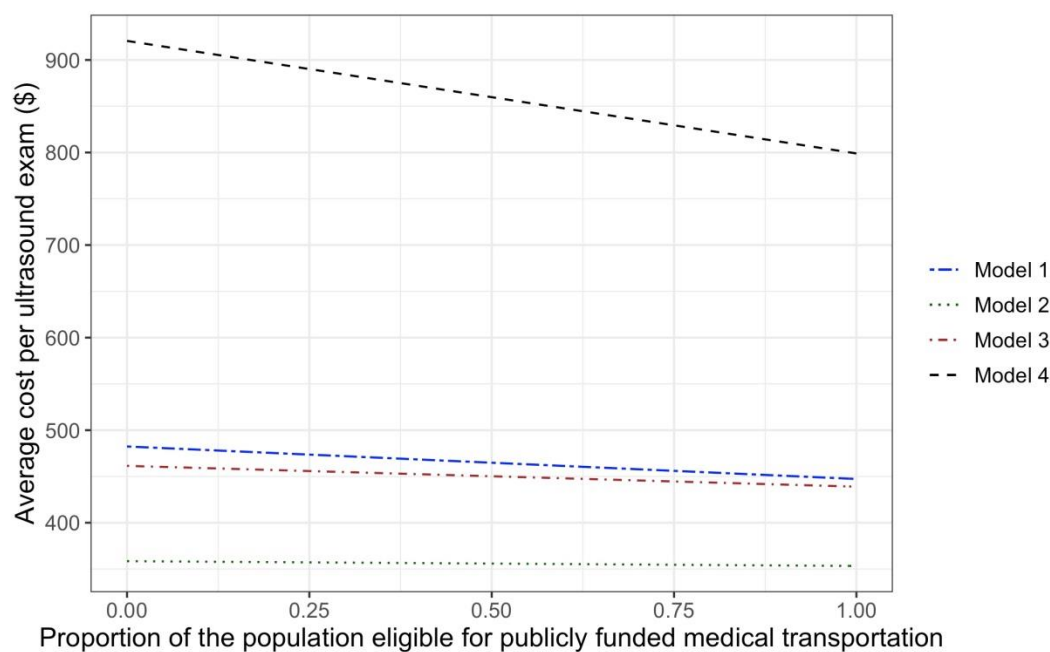
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Figure 9.4. Average cost per ultrasound exam for each ultrasound service delivery model from a (A) publicly funded healthcare payer perspective and (B) societal perspective as the proportion of the population who are eligible for publicly funded medical transportation (status First Nations persons) varies. All other parameters are held constant in each model.

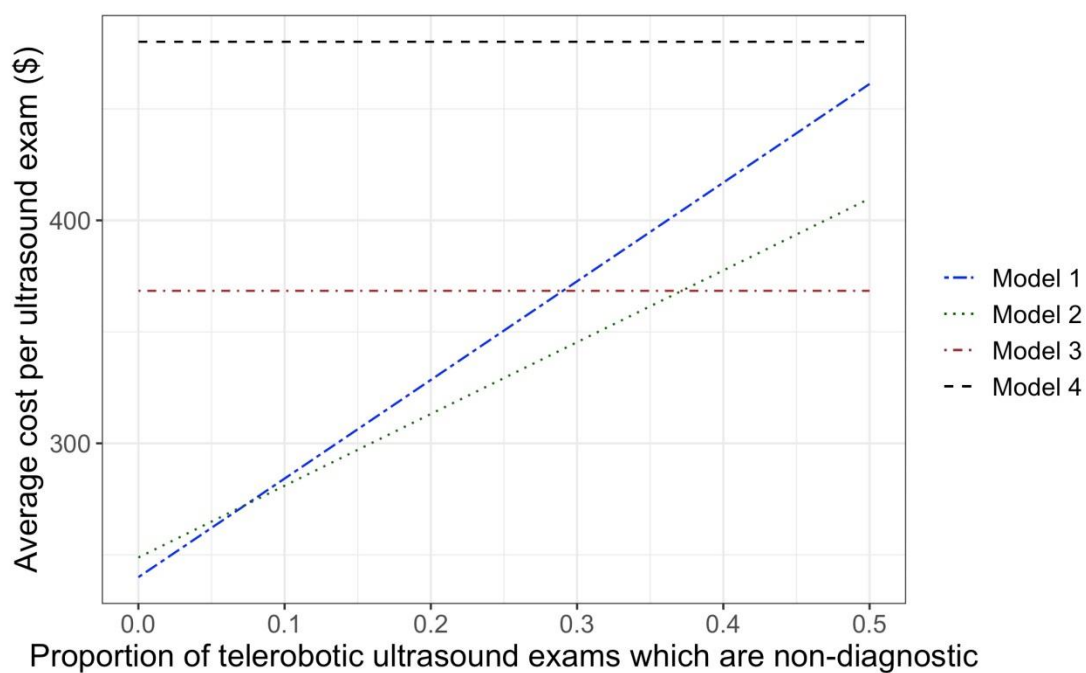
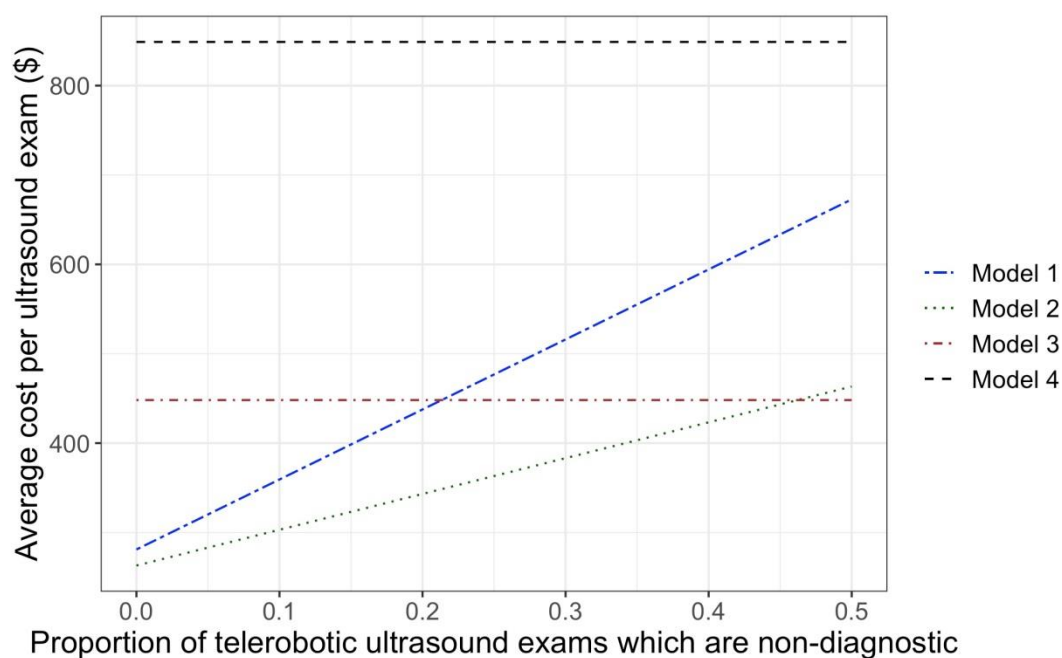
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Figure 9.5. Average cost per ultrasound exam for each ultrasound service delivery model from a (A) publicly funded healthcare payer perspective and (B) societal perspective as the proportion of telerobotic ultrasound exams which are non-diagnostic and are recommended to be repeated conventionally varies. All other parameters are held constant in each model.

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 9.6A). 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 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. The cost of Model 3 increased to approach approximately the average cost per ultrasound exam in Model 4 as a greater proportion of patients had to travel for an ultrasound exam. The average cost per ultrasound exam in Models 1 and 4 were constant as these models did not include an itinerant sonographer service.

9.4.2 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 9.4). In a one-way sensitivity analysis as community population size varied, Model 3 (itinerant sonographer) was the lowest cost model for communities with less than 1510 people (Figure 9.2B). For communities with greater than or equal to 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 9.3B). For communities >350 km, Model 2 (telerobotic ultrasound with an itinerant sonographer) was the lowest cost model. Across all proportions of the population which are eligible for publicly funded medical transportation, Model 2 was the lowest cost model (Figure 9.4B).

In the one-way sensitivity analysis as the proportion of telerobotic exams which were non-diagnostic varied, Model 2 was the lowest cost model if the proportion of non-diagnostic

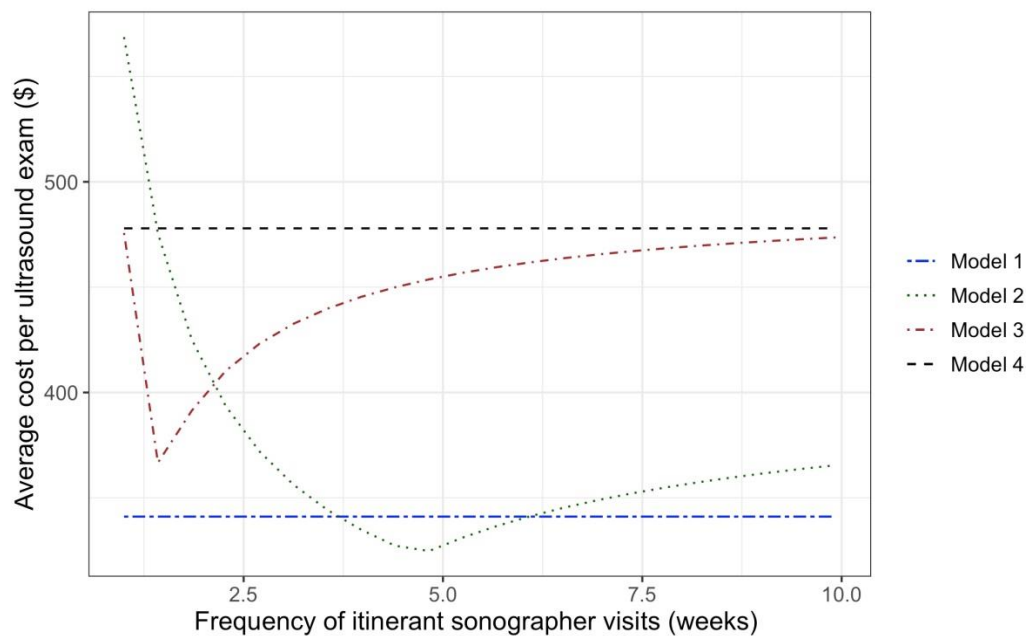
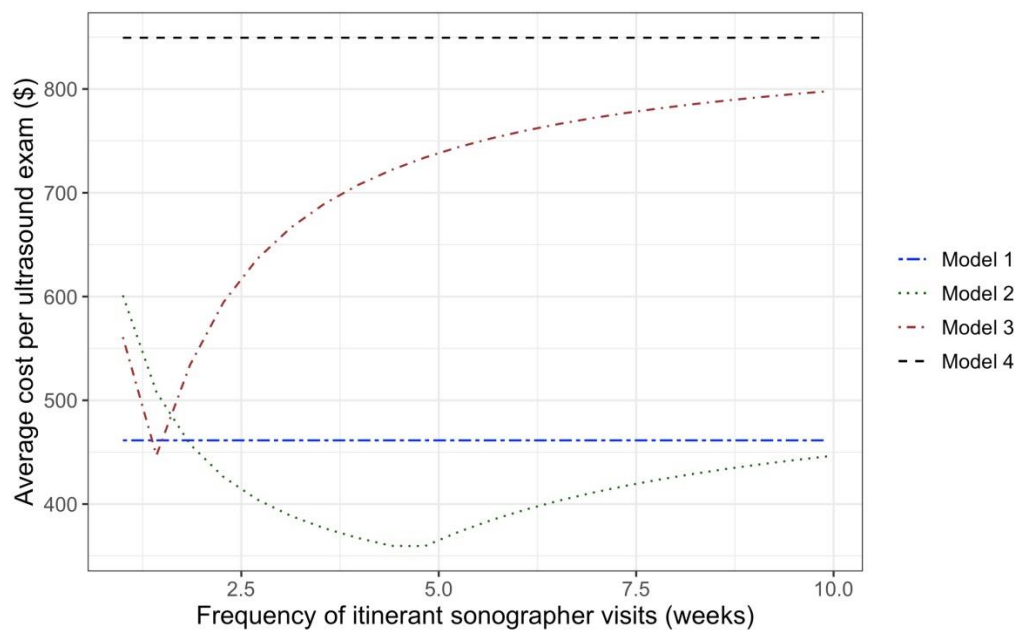
A**B**

Figure 9.6. 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 frequency of itinerant sonographer visits varies. All other parameters are held constant in each model.

telerobotic ultrasound exams was less than 47% (Figure 9.5B). Model 3 was the lowest cost model if 47% or more of all 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 9.6B).

9.5 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. Specifically, one-way sensitivity analyses showed that providing ultrasound services using telerobotic ultrasound combined with an itinerant sonographer was the lowest cost option from a payer perspective for communities with >2075 people, distance >350 km from the nearest ultrasound facility, or >47% of the population eligible for publicly funded medical transportation, and was the lowest cost option from a societal perspective for communities with >1510 people and distance >350 km from the closest ultrasound facility, regardless of the proportion of the population eligible for publicly funded medical transportation. 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. For communities with higher population size, the substantial difference in average cost per exam between Models 1-3 (which incorporated telerobotic ultrasound and/or an itinerant sonographer) and Model 4 (which relied on patients traveling for all ultrasound exams) primarily reflected reduced transportation costs in Models 1-3 relative to Model 4.

Prior to this study, limited evidence existed regarding the cost implications of telerobotic ultrasound. 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.¹²⁸ The authors concluded that the substantial reduction in patient travel time and cost provided justification for further investigation into this model of care.¹²⁸ In our study we 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. There is also limited evidence regarding the cost implications of having an itinerant sonographer provide ultrasound services in rural and remote communities. A study in Sweden found that a mobile X-ray unit which served primarily nursing home residents across 10 municipalities was less costly from a societal perspective and health system perspective than having patients travel to a hospital for X-ray imaging.²⁷² Our study provides evidence suggesting that an itinerant ultrasound service may also be less costly than requiring patients to travel for all ultrasound exams.

Parallels can also be drawn to economic analyses of teleradiology, which allows radiologists to remotely interpret images, but is reliant on technologist presence at the patient-site to acquire images. As picture archiving and communications systems (PACS) were initially implemented, studies compared costs associated with radiologists traveling to a remote hospital to interpret studies compared to radiologists remotely reading exams via PACS. Results varied based on the volume of imaging exams performed and equipment life expectancy, though teleradiology generally resulted in cost savings.²⁵⁷ This is similar to our study in that given

sufficient imaging volume, investment in technological infrastructure is more economical than expenditures towards travel for patients or sonographers. Another study which found that implementing a teleradiology solution did not reduce costs in the study community concluded that such a solution could be justified on the basis of equity of access and quality of care.²⁵⁶

While this economic analysis provides important information to inform decisions surrounding ultrasound service delivery in rural and remote communities, other considerations should also be taken into account to ensure equitable and patient-centred care. A significant benefit of remote presence technologies such as telerobotic ultrasound is that patients can remain in their home community for ultrasound, minimizing time away from family and allowing their family to participate in their care. Our prior research described many challenges which 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 favourability 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. During a COVID-19 outbreak in La Loche, Saskatchewan, telerobotic ultrasound allowed our team to remotely provide obstetrical ultrasound services, minimizing the need for patient travel during the outbreak and negating the need for a sonographer to travel to the community during the outbreak.¹⁶⁸ These additional benefits of telerobotic ultrasound should be considered as part of a comprehensive analysis of providing ultrasound services to rural and remote populations.

Contextual factors are critical to consider when determining an optimal solution for ultrasound service delivery for specific communities, and in Indigenous communities, community self-determination should be considered.²⁷³ 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. Our analysis assumed that telerobotic ultrasound services would be available 24/7 (i.e. on an on-call basis after-hours). 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.

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 capital cost of purchasing 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.^{31,274}

As telerobotic technology evolves, it will likely become increasingly feasible to perform additional types of ultrasound exams telerobotically. Our analysis was limited to abdominal, pelvic, renal, superficial soft tissues, and obstetrical (first trimester, limited second trimester, and third trimester) exams. As clinical studies validate telerobotic ultrasound for additional types of ultrasound exams, such as musculoskeletal ultrasound exams, incorporating these types of exams into economic analyses will be needed. 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 as demonstrated in Figure 9.5.

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. While sensitivity analyses (varying population size, distance to the closest ultrasound centre, and proportion of individuals eligible for publicly funded medical transportation) aim to bring relevance of findings to other rural and remote communities, characteristics of all communities

are not directly considered, and results may not be generalizable to all communities. 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. Further, 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. To help represent uncertainty in model parameters and cost estimates, probabilistic analysis was conducted, demonstrating relatively wide confidence intervals for each of the cost estimates. Additionally, the analysis did not incorporate additional costs which may be incurred for cases performed after hours, such as overtime or call stipends; however, these additional costs are anticipated to be equal across all models. 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. Additionally, while our analysis incorporated the proportion of telerobotic ultrasound exams which are non-diagnostic, it did not incorporate the smaller proportion of conventional ultrasound exams which are non-diagnostic due to various factors such as bowel gas or body habitus. Thus, in the relative comparison of ultrasound service delivery models as presented in Figure 9.5, the proportion of telerobotic ultrasound exams which are non-diagnostic may best be considered the incremental proportion of non-diagnostic telerobotic ultrasound exams over and above the proportion of non-diagnostic conventional ultrasound exams. Fourth, our study assumed equivalent health outcomes across all ultrasound service delivery models and a cost-minimization analysis was chosen as the study design. However, further empirical research to determine if and how outcomes may differ across ultrasound service delivery models is suggested, following which a cost-effectiveness or cost-utility analysis is recommended.

9.6 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, with consideration given to community population size, distance to the nearest ultrasound facility, and available health human resources. Collaboration with community leaders will be important to determine solutions which best serve each community, with consideration given to cost and dimensions of patient access. Finally, 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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CHAPTER 10

DISCUSSION*

10.1 Contributions of this thesis

This thesis makes several significant contributions to the diagnostic radiology, virtual care and telemedicine, and health services literature. The thesis provides improved understanding of gaps in access to ultrasound imaging in underserved northern, remote communities, and advances and validates a novel technology to address these gaps and ultimately improve patient care. The research studies comprising this thesis have important implications for the delivery of health services. The results of this research enable radiology leaders, health system decision makers, policy makers, and Indigenous leaders to make better informed evidence-based decisions to improve access to medical imaging in currently underserved areas, including through the implementation of novel technologies.

The first research study in this thesis, presented in Chapter 3, provides increased understanding of factors which shape access to ultrasound imaging in northern, remote communities, an area which has been largely unexplored in the literature. Insights obtained from this study are invaluable in informing future patient-centred approaches to improve access to ultrasound imaging—and more broadly, medical imaging—in northern, remote communities. The qualitative methodology employed in Chapter 3 provides an example of how this methodology—rarely used in the diagnostic radiology literature—can be used to inform efforts to improve health equity in medical imaging.

Chapters 4 and 5 found that some of the barriers to *access* ultrasound imaging, such as geographic remoteness, were reflected as decreased rates of *utilization* of ultrasound imaging. Substantial disparities in ultrasound imaging were identified among individuals living in rural and remote communities, Indigenous persons, and individuals living in low income neighbourhoods. The findings from these studies send an urgent call to health system leaders and policy makers to address issues of ultrasound access in rural, remote, and Indigenous communities in order to improve health equity.

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Telerobotic ultrasound was subsequently explored as a novel technology to address a key barrier for patients accessing ultrasound imaging as identified in prior chapters—geographic remoteness from ultrasound facilities. By improving access to ultrasound imaging, this technology could potentially reduce disparities in ultrasound utilization in northern, remote communities. The clinical trial presented in Chapter 6 validates a telerobotic approach for obstetrical ultrasound imaging and helps inform future technological development.

The mixed-methods study in Chapter 7 evaluating telerobotic ultrasound as a potential service delivery model to remotely provide ultrasound services serves as the first real-world clinical exploration of telerobotic ultrasound technology in North America. The study provides radiology leaders with important insights regarding telerobotic ultrasound in the domains of diagnostic assessment, patient experience, and health system and radiology practice integration. These insights are critical to radiology and health system leaders to make evidence-informed decisions regarding the deployment of telerobotic ultrasound systems in northern, remote communities.

As presented in Chapter 8, our team’s research on telerobotic ultrasound allowed us to provide critical ultrasound services during a COVID-19 outbreak in a remote community. Our evaluation of the provision of telerobotic ultrasound services during the pandemic suggested that telerobotic ultrasound can be used to answer focused clinical questions such as fetal viability, dating, and fetal presentation in a timely manner while minimizing the need for patient travel and potential exposure to SARS-CoV-2. As exemplified by the use of this technology during the COVID-19 pandemic, the advancement of telerobotic ultrasound technology holds the potential to reduce health inequities in underserved communities.

Finally, the economic evaluation presented in Chapter 9 comparing various models of ultrasound service delivery found that telerobotic ultrasound combined with an itinerant sonographer was the lowest cost option given the current cost structure of telerobotic ultrasound from a publicly funded healthcare payer perspective and societal perspective for a range of community characteristics. Results provided in Chapter 9 are valuable for health system decision makers and community leaders in determining the economic implications of current and alternative methods of ultrasound service delivery, providing evidence to inform fiscally responsible decisions. The various models of ultrasound service delivery which are compared provide Indigenous leaders with a range of options to determine what is best for their

community, such that healthcare services are provided in a *good way*—in a culturally safe manner which meets the needs of each unique community.

10.2 Practical implications for improving access to ultrasound imaging in northern, remote communities

The challenges that patients in northern, remote communities face in accessing ultrasound imaging, disparities in ultrasound imaging utilization among Indigenous persons and individuals residing in rural and remote areas and low income neighbourhoods, and disparities in health outcomes between northern and non-northern and between Indigenous and non-Indigenous peoples implore health system leaders to explore solutions to improve health equity. This includes exploring solutions to improve access to ultrasound imaging.

Results presented in this thesis suggest that telerobotic ultrasound may be a viable solution to address ongoing challenges faced by patients and health systems in northern, remote communities. Most patients who had a telerobotic ultrasound at one of the three pilot telerobotic ultrasound clinics could remain in their home community for an ultrasound exam, minimizing travel to another community for ultrasound imaging and the challenges associated with travel. Sonographers performed exams from an urban centre, minimizing challenges associated with sonographer recruitment and retention in northern and remote communities. Patient-site assistants were recruited from local northern, remote communities, providing a local connection to support culturally safe care. Using telerobotic ultrasound technology, patients could access specialist imaging services which are currently available only in an urban centre. The economic evaluation suggested that telerobotic ultrasound combined with an itinerant sonographer is the lowest cost option across a range of community characteristics from a health system perspective and societal perspective.

However, current limitations of telerobotic ultrasound must also be acknowledged. Telerobotic ultrasound resulted in diagnostic exams for most abdominal, first trimester obstetrical, limited obstetrical, and renal ultrasound exams, though results suggest that due to the high proportion of second trimester obstetrical ultrasound exams which were recommended to be repeated, this type of exam should not be performed using current telerobotic ultrasound systems. The substantial proportion of pelvic exams which were recommended to be repeated, together with the inability to perform endovaginal scanning, suggest that pelvic ultrasound

exams may also best be performed conventionally. However, the small number of pelvic exams performed as part of the study limits conclusions which can be drawn and is an area for future research. In addition to limitations due to telerobotic technology, ultrasound exams were significantly limited by patient factors such as body habitus and early or late gestational age. Careful patient selection will be a key aspect to consider going forward to help ensure that patients receive the most appropriate type of exam—telerobotic or conventional—particularly if there is a high likelihood that a telerobotic ultrasound exam will be non-diagnostic.

Telerobotic ultrasound systems have received regulatory approval in many countries, providing radiology groups and radiology departments with an opportunity to deploy telerobotic ultrasound systems in communities without ultrasound services. Telerobotic ultrasound systems may be deployed by publicly-funded healthcare delivery organizations (e.g. provincial health authorities), private radiology groups, or First Nations healthcare organizations, for example. The development of a “hub and spoke” model which brings patients from neighbouring remote communities to a telerobotic ultrasound clinic may increase the catchment area for telerobotic ultrasound clinics, thereby increasing patient volume, decreasing the per-exam cost of telerobotic ultrasound, and helping to justify the initial capital investment of a telerobotic ultrasound system. A network of telerobotic ultrasound systems served by a radiology group may provide a sufficient volume of exams to allow telerobotic ultrasound to be integrated into the routine operations of a radiology group, allowing the group to develop expertise in best practices related to telerobotic ultrasound and find efficiencies in operations. Physician reimbursement will be a key determinant regarding the sustainability of telerobotic ultrasound as a model of ultrasound service delivery.

While the economic evaluation included in Chapter 9 suggested that telerobotic ultrasound combined with an itinerant sonographer is the lowest cost option across a range of community characteristics from a publicly funded healthcare payer perspective and societal perspective, individual community factors are important to consider when determining an optimal solution for ultrasound service delivery. It is important to assess sonographer and radiologist availability for itinerant or telerobotic ultrasound clinics, availability of reliable transportation for sonographers, community population size, and proximity to other ultrasound facilities, as each of these factors have important implications regarding the feasibility and relative cost associated with a telerobotic ultrasound service. Additionally, developing

collaborative relationships with Indigenous peoples is a critical aspect to allow Indigenous communities determine what is best for their community.

As the three telerobotic ultrasound clinics were developed, a number of challenges were encountered which may be informative to highlight for other groups deploying telerobotic ultrasound systems. Delays in deployment and integration into RIS and PACS due to organizational processes (as health system administrators were cautious because of uncertainty and unknown risks associated with telerobotic ultrasound), intermittent malfunction of the telerobotic ultrasound system requiring IT support, and variable lag time for the robotic control and ultrasound images were some of the challenges experienced. Common themes among approaches used to successfully overcome these obstacles included drawing upon a multidisciplinary team, engaging senior health system leadership and local healthcare providers in the remote communities, and establishing respectful, collaborative relationships with each of the Indigenous communities in which we established telerobotic ultrasound clinics. Some ongoing limitations should also be noted, the foremost of which is that telerobotic ultrasound clinics at the time of writing are not at the frequency needed to meet community demand due to limited sonographer availability. This challenge emphasizes the need to ensure sonographer human resources are available before launching new sites to ensure that community trust and satisfaction continues to be fostered through a reliable, regularly available telerobotic ultrasound service.

With the significant rise of virtual care during the COVID-19 pandemic, there are increased expectations from patients that virtual care continues to become integrated within the healthcare system and becomes a core aspect of healthcare delivery after the pandemic.²⁷⁵ It will be important for healthcare leaders to consider the technologies which have enabled patient-centred care during the COVID-19 pandemic, and build upon the momentum and policy changes supporting virtual care integration and reimbursement as a result of the pandemic.^{275,276} The broad adoption of virtual care for primary and specialty care during the COVID-19 pandemic may serve as a catalyst to support the implementation of imaging technologies which bring care closer to patients, thereby removing barriers for patients to access care and improving the patient experience.

Access to ultrasound services is a multidimensional concept, and other aspects of access to ultrasound services beyond geographic proximity to ultrasound services should also be

considered. As discussed in Chapter 3, proactively contacting patients to re-book cancelled or missed exams, facilitating childcare during ultrasound appointments, offering extended hours for patients with family and work responsibilities, providing timely appointments for imaging, and providing culturally safe care facilitated by local health care providers are potential solutions to support access to ultrasound services. It is critical to ensure these other aspects of access beyond geographic accessibility are considered to ensure patient-centred care, regardless of whether ultrasound services are provided using telerobotic or conventional ultrasound.

10.3 Future research directions

Our experience in using telerobotic ultrasound for abdominal, pelvic, and obstetrical exams has provided insights into current limitations of telerobotic ultrasound systems and areas where further research and development is suggested. Continued advances in robotics and the establishment of 5G telecommunication technology will help advance telerobotic ultrasound systems and help address some of the limitations of current telerobotic ultrasound systems. Increased DOFs to allow the sonographer to control sliding and compression may reduce exam times and improve image quality; a smaller footprint for the frame of the probe holder could help improve visualization of organs for which significant angulation of the ultrasound probe is required; and modifications to the supporting frame of the probe holder may reduce potential musculoskeletal injury for patient-site assistants.⁵⁴ Incorporation of haptic technology to telerobotic ultrasound could provide the expert sonographer additional tactile information while performing the exam. Consideration should also be given to movement of the body surface during breathing, for example, to ensure the telerobotic ultrasound system complies with the natural movement of the body surface and ensure the probe maintains continuous contact with the body surface.⁹³ The development of telerobotic ultrasound systems for currently unmet needs, such as musculoskeletal ultrasound, is another opportunity for advancement. The unique anatomy of the upper and lower extremities provides a smaller surface area for scanning than required for abdominal and obstetrical scanning, suggesting that dedicated supporting frames and/or manipulators may help meet these needs. There may also be interest in exploring remote vascular ultrasound, particularly in cases that require urgent or emergent imaging such as in the assessment of possible deep venous thrombosis.

Adaptation of non-dedicated commercialized robotic arms for telerobotic ultrasound may decrease development costs and potentially bring new vendors to the market, though regulatory requirements will be key considerations. Since remote control of ultrasound unit settings and functions is currently available from only specific vendors, entry of or partnership with major medical imaging vendors will broaden the range of ultrasound units which can be easily used with telerobotic ultrasound systems, potentially improving image quality. While efforts in telerobotic ultrasound have primarily focused on solutions which allow sonographers to remotely manipulate an ultrasound probe, development of autonomous ultrasound scanning, most established in the area of automated breast ultrasound,²⁷⁷ is another area for further advancement. Analysing force and ultrasound image data together in real-time using deep learning, similar to that recently used for vertebral level localization,²⁷⁸ may be a promising approach towards autonomous ultrasound scanning.

To expand the market for telerobotic ultrasound systems beyond rural and remote communities, developers may wish to consider the potential of telerobotic ultrasound as an ergonomic solution to reduce musculoskeletal strain among sonographers. Work-related musculoskeletal disorders are particularly prevalent among sonographers, with studies indicating that approximately 90% of sonographers report musculoskeletal pain or discomfort while scanning.^{279,280} Injuries can be exacerbated by scanning patients with high body mass index, as a greater amount of pressure is applied when scanning these patients.²⁸¹ Telerobotic systems to reduce the forces that must be applied by sonographers and facilitate more ergonomic positioning while scanning may help reduce musculoskeletal injuries among sonographers.

Beyond telerobotic ultrasound, additional innovative technologies should be explored to provide ultrasound services in northern, remote communities. Real-time remotely mentored ultrasound—allowing an expert to view ultrasound images as they are acquired in real-time and provide guidance to a local operator using a handheld ultrasound probe—may be a low-cost option for some clinical settings and for some clinical indications. Additionally, the potential for artificial intelligence (AI) to be used to guide users in assessing all required anatomy is another promising future area for research. While work in this area to date has largely focused on echocardiography,²⁸² AI-assisted ultrasound for obstetrical imaging is another particularly promising area for further development. In addition, continued advances in 3D ultrasound acquisitions (volume ultrasound imaging) may reduce the operator dependent nature of

ultrasound and allow a broader range of users to acquire ultrasound images,²⁸³ including healthcare providers in northern, remote communities.

Our study investigated telerobotic ultrasound in only three northern Saskatchewan communities with radiologists from a single academic hospital. Further work should include a multi-centre trial to determine the diagnostic potential of the technology and its generalizability as a feasible solution as it is scaled up across multiple sites. As Chapters 4 and 5 found lower ultrasound utilization rates among patients in remote communities, potentially as a result of decreased accessibility to ultrasound facilities for these patients, determining any changes in ultrasound imaging utilization as telerobotic ultrasound is introduced in the community is another important aspect for further investigation. In addition, assessing the appropriateness of ultrasound referrals is an important next step to ensure that the introduction of a more readily accessible imaging modality does not result in an increase in referrals not meeting appropriateness criteria. Future work should determine where additional supports for ultrasound imaging are most needed based on current imaging utilization data and population characteristics such as population age, comorbidities, and birth rates, with a view to deploy telerobotic ultrasound systems in areas of greatest need and greatest disparities in ultrasound utilization.

Additional work should explore the feasibility of using telerobotic ultrasound to improve access to ultrasound imaging in resource-poor settings around the world. Comparison of multiple approaches of providing ultrasound services, including telerobotic ultrasound, real-time remotely mentored ultrasound, AI-assisted ultrasound, and/or increased ultrasound training for local healthcare providers will be helpful to determine optimal solutions for specific clinical settings. For example, while telerobotic ultrasound may not be an optimal solution in some settings due to IT requirements, other solutions such as real-time remotely mentored ultrasound or AI-assisted ultrasound may better assist local healthcare providers in offering ultrasound imaging to their patients.

This thesis also lays the groundwork for a research program with the broader aim of improving health equity in medical imaging. While this thesis focused on telerobotic technology as a solution to improve access to ultrasound imaging, there is a critical need to consider health equity in medical imaging across imaging modalities. A multifaceted approach including the development, evaluation, and implementation of solutions to improve access to imaging care in

its multiple domains will be critical to ensure that healthcare systems meet the needs of populations in a sustainable manner.

10.4 Conclusion

This thesis provides key insights for health system leaders seeking improved understanding and novel solutions to improve access to ultrasound imaging in northern, remote communities. Findings suggest that telerobotic ultrasound is a viable solution to improve access to ultrasound imaging for northern, remote communities and reduce costs associated with ultrasound service delivery. Evidence in this thesis may be used to help improve ultrasound services and health equity for patients in northern, remote communities. Research in this thesis emphasizes the need for the radiology community to explore disparities in medical imaging and develop solutions to improve health equity. Respectful collaboration with Indigenous peoples will be critical to ensure that efforts to improve imaging care are done in a good way and that medical imaging services truly meet the needs of northern, remote populations.

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APPENDIX

This thesis is based on the following eight manuscripts which have been published or accepted for publication in peer-reviewed journals or are currently undergoing peer review. All of the journals in which these manuscripts have been accepted or published have policies which provide permission for these manuscripts to be reproduced in this thesis. Publication status and author contributions are described below.

Manuscript A.

Adams SJ, Burbridge B, Obaid H, Stoneham G, Babyn P, Mendez I. Telerobotic sonography for remote diagnostic imaging: narrative review of current developments and clinical applications. *J Ultrasound Med.* 2021;40(7):1287-1306. doi: 10.1002/jum.15525.

Author contributions: Dr. Adams developed the search strategy, performed the literature search, and wrote the manuscript. Drs. Burbridge, Obaid, Stoneham, Babyn, and Mendez revised the manuscript for important intellectual content.

Manuscript B.

Adams SJ, Babyn P, Burbridge B, Tang R, Mendez I. Access to ultrasound imaging: a qualitative study in two northern, remote, Indigenous communities in Canada. *Int J Circumpolar Health.* 2021;80(1):1961392. doi: 10.1080/22423982.2021.1961392.

Author contributions: Dr. Adams conceived the idea for and designed the study, led development of the interview guide, oversaw the process of conducting interviews, led data analysis, and wrote the manuscript. Drs. Babyn, Burbridge, and Mendez revised the manuscript for important intellectual content. Ms. Tang contributed to development of the interview guide, conducted interviews, assisted with data analysis, and revised the manuscript for important intellectual content.

Manuscript C.

Adams SJ, Yao S, Mondal P, Lim H, Mendez I, Babyn P. Sociodemographic and geographic disparities in obstetrical ultrasound imaging utilization: a population-based study. *Acad Radiol*. 2021. doi: 10.1016/j.acra.2021.07.012 (online ahead of print)

Author contributions: Dr. Adams conceived the idea for and designed the study, developed the protocol for statistical analysis, interpreted the data, and wrote the manuscript. Mr. Yao extracted data from administrative databases, conducted statistical analysis, and revised the manuscript for important intellectual content. Dr. Mondal and Dr. Lim provided guidance on statistical analysis and revised the manuscript for important intellectual content. Dr. Mendez and Dr. Babyn revised the manuscript for important intellectual content.

Manuscript D.

Adams SJ, Yao S, Mondal P, Lim H, Mendez I, Babyn P. Sociodemographic and geographic factors associated with non-obstetrical ultrasound imaging utilization: a population-based study. *Can Assoc Radiol J*. (accepted)

Author contributions: Dr. Adams conceived the idea for and designed the study, developed the protocol for statistical analysis, interpreted the data, and wrote the manuscript. Mr. Yao extracted data from administrative databases, conducted statistical analysis, and revised the manuscript for important intellectual content. Dr. Mondal and Dr. Lim provided guidance on statistical analysis and revised the manuscript for important intellectual content. Dr. Mendez and Dr. Babyn revised the manuscript for important intellectual content.

Manuscript E.

Adams SJ, Burbridge BE, Badea A, Kanigan N, Bustamante L, Babyn P, Mendez I. A crossover comparison of standard and telerobotic approaches to prenatal ultrasound imaging. *J Ultrasound Med*. 2018;37(11):2603-2612. doi: 10.1002/jum.14619.

Author contributions: Dr. Adams designed the study, developed the data collection instruments, oversaw study conduct including participant recruitment and data collection, performed the statistical analysis, and wrote the manuscript. Dr. Burbridge provided guidance on study design and study conduct, provided ultrasound interpretations, and revised the manuscript for important intellectual content. Ms. Badea and Ms. Kanigan assisted with participant recruitment and data collection. Mr. Bustamante provided technical assistance. Dr. Mendez and Dr. Babyn provided guidance on study design and study conduct and revised the manuscript for important intellectual content.

Manuscript F.

Adams SJ, Burbridge B, Chatterson L, Babyn P, Mendez I. A telerobotic ultrasound clinic model of ultrasound service delivery to improve access to imaging in rural and remote communities. *J Am Coll Radiol.* (accepted)

Author contributions: Dr. Adams designed the study, oversaw study conduct including participant recruitment and data collection, performed the statistical analysis, and wrote the manuscript. Dr. Burbridge and Dr. Chatterson provided guidance on study design and study conduct, provided ultrasound interpretations, and revised the manuscript for important intellectual content. Dr. Mendez and Dr. Babyn provided guidance on study design and study conduct and revised the manuscript for important intellectual content.

Manuscript G.

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Author contributions: Dr. Adams designed the study, oversaw study conduct including participant recruitment and data collection, performed the statistical analysis, and wrote the manuscript. Dr. Burbridge and Dr. Chatterson provided guidance on study design and study

conduct, provided ultrasound interpretations, and revised the manuscript for important intellectual content. Drs. McKinney, Babyn, and Mendez provided guidance on study design and study conduct and revised the manuscript for important intellectual content.

Manuscript H.

Adams SJ, Penz E, Imeah B, Burbridge B, Obaid H, Babyn P, Mendez I. Economic evaluation of telerobotic ultrasound technology to remotely provide ultrasound services in rural and remote communities (currently undergoing peer-review)

Author contributions: Dr. Adams developed the study methodology, performed data analysis, and wrote the manuscript. Dr. Penz provided guidance on study methodology and revised the manuscript for important intellectual content. Ms. Imeah contributed to data analysis and revised the manuscript for important intellectual content. Drs. Burbridge, Obaid, Babyn, and Mendez reviewed and revised the manuscript for important intellectual content.