Adapting Collaborative Radiological Practice to Low-Resource Environments

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ABSTRACT
We describe how current radiological best practices are predicated on a sophisticated technological ecosystem usually comprised of multiple large-scale displays, and integrated record keeping and communication systems driven by high-speed networks. At the same time, current development of low-cost ultrasound (U/S) devices for low-resource settings trends towards small-scale, independent devices with palm-sized screens. We reviewed existing literature, analyzed findings from two years of fieldwork in Uganda, and conducted an interview study with clinicians about radiology work practices to determine which patterns and technologies contribute to the efficacy of ultrasound. We use these findings to inform how ultrasound technology in low-resource settings can most usefully be developed and deployed. In addition, findings are relevant for creating medical technologies for low-resource environments generally, as we make clear the importance of considering not just technology development aspects like power consumption and interface, but also larger technology and work ecosystems.

Author Keywords
ICTD, Radiology information systems, PACS, Professional practice, Teleradiology, Medicine, CSCW

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Human Factors; Design.

CSCW'12, February 11–15, 2012, Seattle, Washington, USA.

INTRODUCTION
There is a growing interest in how low-cost medical technologies can be developed and deployed in low-resource settings to improve global health indicators. Tools such as low-cost, point-of-care technologies (e.g. microfluidic diagnostic systems [35], mobile phone based microscopes [4], and phone-based cough detection [17]) have inspired new research approaches and interdisciplinary research communities. This global health research community shares many of its approaches with the information and communication technologies for development (ICTD) field, an emerging area of research focused on using computer-based solutions to address problems facing developing regions and underserved populations, including problems associated with collaborative practices in the workplace. In addition to healthcare applications, ICTD projects focus on a wide variety of problem spaces, such as education, agriculture, microfinance, and transportation [1, 11, 18, 24, 33]. Many lessons have been drawn from the successes and failures of ICTD research, most of which emphasize the importance of creating and deploying technologies that recognize the physical settings in which people live and work [2, 7, 20]. For example, ICTD researchers have identified a common set of design and computing constraints such as cost, low power, low connectivity, low literacy, multiple or marginalized languages, and accessibility challenges [12].

In addition to design issues focused on technological artifacts, researchers in the ICTD community have also learned to design with a focus on people and diverse usage contexts. Such work tends to be informed by social construction of technology and appropriate technology literature [26, 13]. Appropriate technology literature advocates for design that meets ethical, cultural, social, political and economic standards in the community for which it is intended. Leveraging existing systems, processes, and resources rather than trying to introduce radically new ones can help researchers design and deploy appropriate technology.

Our work builds on these foundations, in addition to central HCI literature and scholarship on design for resource-constrained environments [16, 19]. In addition, our work has been informed by the central concerns of the CSCW community, including work practices, place and space, and articulation work [34, 9, 29]. To this end, we have built our research with a focus on the differences in group work and socio-technological barriers that come to bear on ultrasound usage, and we expand upon notions of CSCW in Western-country contexts to users in developing regions.

For the past two years, informed by fieldwork in Uganda and the theoretical traditions mentioned above, we have been designing a portable maternal ultrasound (U/S) system for midwives in the developing world. Midwives—trusted and central figures within Uganda's existing healthcare system—are an appropriate audience for our system as they are the critical link between rural healthcare centers and referral hospitals that offer more comprehensive treatment options. It is our goal that this system (called the Ultrasound PLUS, — Portable, Learning- and User-centered System) will leverage Uganda's existing referral network and ensure that women with high-risk obstetrical (OB) conditions receive appropriate follow-up care. The Ultrasound PLUS also features an integrated Help system.

In our past work, we have tried to build technologies that adapt to existing patterns of trust and confidence, information-seeking practices, and technology usage within communities [27]. The consideration of workplace collaboration, however, is an additional constraint. Indeed, often missing from existing ICTD research and practice is an understanding of how technology-based work practices are affected when the technological ecology of those practices is changed. Collaboration that is not explicitly part of a job often provides a crucial means of domain learning, task efficiency, and general enculturation. Whether or not a technology supports these hidden work practices [30] can impact the success of an intervention.

U/S is widely used in the developed world. However, these contexts almost exclusively have multiple practitioners, technology-centric work practices, and multiple communication tools. Prior CSCW work in the medical domain speaks to such characteristics by exploring issues of information workflow and adapting interfaces, highlighting face-to-face communication, and the complexity of information needs as drivers of multi-layered collaboration [28]. Health specialists, operating under the strain of complex and ambiguous information flows, must continuously engage in group sense-making to collectively interpret and take action on patient data [25]. These teams utilize rapid feedback, shared context, and exposure to nuanced information for collective decision-making [23].

CSCW patterns, like those mentioned above, emerge in part from the interplay between technologies in place and work practices [8]. Our work with low-cost U/S recognizes that we cannot replicate all of the characteristics of work practice and space seen in developed world settings, and our design efforts must recognize and compensate for the changes in the larger technology ecology. Design in low-resource contexts poses unique challenges in assessing the patterns of relationships between a physical space and socio-technical conditions in which tools are used. In particular, new issues surrounding the role of mobile U/S technology arise; as circuits of mobility intersect and overlap in space [9], traditional midwifery work practices, patterns of trust, and power dynamics are altered.

In developing medical technologies for low-resource environments, the ICTD community has well-established techniques for adapting technologies. But less attention is paid to work context—how technical functionality actually scaffolds certain work practices, and this area is one we emphasize in our approach. To this end, our designs compensate for limited collaboration potential by building a novel medical help system within the U/S device and supporting existing work practices with minimal interference to the workflow.

BACKGROUND

The ecology and practice of midwifery in Uganda has provided substantial opportunities to rethink conventional workflow models and explore how to bypass resource constraints. Ultrasound—a medical imaging modality used in obstetric care—can be used to identify a variety of conditions that contribute to obstructed labor and hemorrhage at birth. However, we are trying to design a project that deploys ultrasound not just to generic best medical effect, but to best effect given the conditions of maternal care in Uganda.

The work presented in this paper reflects an ethnomethodological approach; researchers such as Brigitte Jordan have also investigated complex, non-Western obstetrics, unearthing the vastly different collaboration patterns that occur in developing-context medicine [14]. In stark contrast to institutionalized medical collaboration in Western medicine, maternal care decisions in developing contexts involve input from a wide spectrum of invested community and family members. These insights help us situate the process of building a technological artifact within those mapped cultural and theoretical concerns.

Our project is affiliated with a larger project within the University of Washington department of Radiology which has been training Ugandan midwives to perform diagnostic U/S exams using commercial stationary U/S devices and portable machines such as the GE LOGIQ Book XP (See Figure 1, Left). Initial work by researchers involved with this project suggests that current commercial devices may be inappropriate for widespread deployment in the developing world [5], and so we sought to design a more appropriate U/S machine (see Figure 1, Right). Our system is built from off-the-shelf technology using a USB probe and a convertible tablet PC.

Figure 1. GE LOGIQ Book XP (left) and Ultrasound PLUS (right). The hardware and UIs differ.

Stationary ultrasound devices, used most commonly for obstetric care in the developed world, generally have advanced features that accommodate a variety of patients and medical conditions, but they are neither power- nor cost-efficient. Current low-cost U/S devices (e.g. GE V-Scan, Mobisante) tend to be small, independent devices with palm-sized screens. Additionally, most U/S devices are designed for advanced medical professionals in hospitals; these devices have complex user interfaces (UIs) and advanced features meant for expert users. They also lack robust help systems. In the United States, a typical U/S technician must undergo training for two years or more [6], which is not feasible for midwives in the developing world due to cost and mobility constraints.

Our design approach has been to reduce functionality to only that which is necessary to detect basic pregnancy complications: depth control, near- mid- and far-gain control, and contrast. Additionally, we have developed an integrated, contextual Help system that guides midwives through best practices in diagnostic U/S, and, through decision trees, assists them in making a diagnosis. The Help system also includes a built-in gallery of images taken by professional sonographers with which midwives can compare their current image. This portion of the design comes from the recognition, through fieldwork and observation, that work settings and training programs in Uganda differ from those in developed world settings.

In other words, our goal is to build an U/S machine that is not only an appropriate technology in terms of the physical design, but one that also matches the constraints on workplace collaboration and cooperation. Some of the questions we address in this paper include: How important is collaboration in the use of U/S? Are there diagnostic or treatment practices that are reliant on the technology ecosystem to the extent that we will not be able to replicate them with our U/S system? Where do radiologists compensate for technologies that don't do what they need? How would they adapt practice if they lost these tools? For more experienced radiologists/sonographers, etc, how does their memory of less technologized work environments compare to current practice?

To answer these questions, we draw on existing literature, two years of fieldwork in Uganda, and an interview study in Seattle to compare the U/S technology ecosystem in Uganda and in the United States. This knowledge will help us design a technology that accommodates differences in work practice and context, and that can be usefully deployed in low-resource settings.

UNDERSTANDING RADIOLOGICAL PRACTICE

Radiologists in the United States rely heavily on picture archiving and communication systems technologies (PACS), which allow them to store and retrieve images, communicate with other radiologists and clinicians, and display and process medical imaging data [11]. As images have transitioned from physical to digital artifacts, they have become distributed across invested medical personnel, allowing each of them greater understanding of how to interpret images. Three-dimensional imaging made it possible to bring multiple images into a single, online volume, simultaneously simplifying and allowing for more sophisticated analysis. The introduction of digital imaging allowed other members of the clinical team to cover traditional radiological tasks, enabling radiologists to invest more time in developing specialized radiological skills. PACS changed the collaboration patterns between radiologists and referring physicians, making that relationship more mediated technologically but also allowing for more collaborative interpretation of imagery.

Other researchers have performed ethnographic studies on the collaborative work practices surrounding PACS to understand the shaping effects of spatial arrangements on work practices. Much of this research focuses on spatial approaches to collaboration by studying work practice and work location, analysis of physical arrangement, and ordering of space in supportive of cooperative work [31]. Our work expands on this discussion by adding a comparison of cooperative work practices in a developed world context using PACS and remote clinics in rural Africa in non-PACS environments.

Teleradiology, a subset of a larger practice called telemedicine, involves the asynchronous transfer of digital images between two or more settings and builds on the premise of PACS. In a teleradiology scenario, local actors typically conduct image acquisition tasks, and remote actors provide interpretive services and/or consultation. Though most studies of teleradiology focus primarily on technical issues, usability issues, or clinical patient outcomes, the work practices surrounding teleradiology have also been the subject of previous CSCW analysis [15]. Karasti, for example, found that teleradiology increased the amount of articulation work done by radiologists as they had to ensure the teleradiology service ran smoothly. For instance, radiologists accustomed to traditional radiological models were used to receiving more contextual information about their patients than that which was typically part of a teleradiology system—including the patient's physical appearance and behavior—and sometimes had to request more information in order to make a confident diagnosis.

U/S—in part because of the ambiguity of the images—often requires more consultations between clinicians and radiologists than other imaging modalities. The need to collaboratively analyze, label and annotate U/S images means these teams rely heavily on robust interaction and consensus building. This two-way interaction ensures accurate image readings and provides the radiologist an opportunity to support the clinician in deciding which additional radiological tests are needed [36].

METHODOLOGY

Our methodology is composed of two pieces: 1) fieldwork in Uganda over the course of two years to understand the context of U/S use for midwives, and 2) interviews with sonographers, radiologists, and clinicians about their collaborative work practices and use of various technologies that enable collaboration. We combine these two approaches in order to demonstrate how the dramatic differences between the two work settings requires careful consideration of how to appropriately develop and deploy U/S technology for low-resource contexts.

Ugandan Fieldwork

Our work is affiliated with a larger project that began at the University of Washington department of Radiology in 2009. Team members from that project—including radiologists, radiology residents, and sonographers—have traveled frequently to Uganda to conduct program evaluations and field observations, including a November 2010 visit to six clinics which generated findings to inform our interview protocol for this study.

In early 2010, our design team surveyed midwives involved in an U/S training program taught by the Ernest Cook Ultrasound Research and Education Institute (ECUREI). Our surveys inquired about those midwives' experience and difficulty with learning current U/S technologies, what constitutes a typical U/S exam, and patient perceptions of healthcare in Ugandan communities [5]. The midwives' responses helped inform both the initial design choices for the U/S system, and the interview protocols we developed for future trips to the field.

In March and July of 2011, six members of our team traveled to Uganda to interview midwives involved in a pilot sonography training program, nursing and midwifery educators, maternal & child health advocates, a traditional birth attendant (TBA), and fifty-two rural mothers split across eight focus groups (results to be discussed in a future paper). Additionally, we visited 15 health centers (a mix of public, private, and private-not-for-profit models) in three districts in Western & Central Uganda to understand the variance in infrastructure, services offered, and patient load.

Below we discuss results from our interviews with midwives that focus on their current work practices and how the introduction of ultrasound is changing those work practices. We also observed the environment in which they conduct their exams and administrative duties, and we conducted usability tests with the current version of the Ultrasound PLUS prototype.

Interviews with Radiologists, Clinicians, and Sonographers

As part of our continuing efforts to understand the ways in which medical imaging supports clinical care, we conducted a total of seven semi-structured interviews with five doctors (three radiologists and two clinicians) and two sonographers in Seattle about their collaborative work practices and the various technologies that enable these collaborations. Participants' experience in the medical field ranged from 2 to 29 years. During some of the interviews we were able to conduct workplace observations of a trauma radiology center, and the U/S department of a large university hospital.

Doctors involved in our study have experience in public and private clinics, and urban and rural clinical settings. Three have experience in international settings. Medical specialties of our participants include trauma radiology, body imaging, family medicine, and high-risk OB. We chose to spread our interviews across the categories of radiologists, clinicians, and sonographers because the Ugandan midwives using U/S in our project act in all three of these roles when they use U/S with their patients.

FINDINGS

We have two groups of findings resulting from the Uganda and the United States fieldwork. This section discusses the themes that emerged from data-driven analyses of these two research activities, and it suggests opportunities for improving our current prototype system so that it better meets the needs of our target audience—midwives and other health workers in Uganda.

Clinical Sites in Uganda

Below is an aggregate example, based on our 2010-2011 interviews with midwives, that provides a scenario for radiological practice in a low-resource environment:

A midwife at a Level 3 Health Center (HC3) arrives in the morning to see women sitting on benches and on the grass surrounding the health clinics. Many women have brought pots of food and luggage with them, knowing that they may have to wait for care for several hours. Many also have small children sitting alongside. The midwife takes a few minutes to talk with all of the women about the benefits of prenatal care before taking one of them to an exam room for a clinical exam. The exam includes taking the patient's history, performing a palpation, and perhaps prescribing a prenatal malaria prophylaxis. Then, the woman is taken to a separate room (a smaller, darker room) for the ultrasound examination. The midwife uses ultrasound to determine the number of fetuses, the position of the fetuses (e.g. breech or heads-down), and the position of the placenta. She may also check for other anomalies and perform measurements. If she has questions, she can use *one of her multiple cell-phones to attempt reach the experienced sonographer at the Level 4 Health Center (HC4); each cellphone holds a SIM card from a different provider, and no single provider has reliable coverage across the district. The midwife records the ultrasound findings in a patient history book that each patient carries with them to the health center. This information is also recorded in paper record books kept locally at the health center. If a pregnancy complication is found, or if the midwife has a question that she cannot resolve, the patient is referred to the HC4 for a follow-up ultrasound.*

Solitary vs. Collaborative Practice

The majority of midwives interviewed (10 out of 12 participants) worked in clinics that employed two midwives and would have one midwife on duty per shift. At two of the five clinics we visited, we encountered other medical staff, including lab technicians and other nurses. The midwives, however, were the only health professionals trained to use the on-site portable U/S unit, meaning that midwives had few opportunities to ask anyone for help acquiring, optimizing, or interpreting U/S images. Midwives were only able to consult others with U/S expertise was the district's sonographic expert (charged with overseeing six clinics in total) dropped by to visit, or if the midwives' shifts overlapped. Occasionally, midwives were able to reach the sonographic expert by telephone. Despite these limited opportunities for communication, midwives often expressed that such communications were vital to their practice. One midwife stated that the two most important people for her in gaining expertise in U/S were the local sonographer and another midwife who worked at the clinic with her. As discussed below, however, consistent telephone connectivity is not a characteristic in most midwives' workplaces. The solitary nature of their work extends to in person as well as technologically mediated exchanges, either synchronous or asynchronous.

The Work Environment

All of the midwives interviewed worked long shifts at the clinics, frequently up to 12 hours. Over the course of a single week, we witnessed two different midwives work over 20 hours continuously. Each clinic we visited employed between one and six midwives, though midwives are often absent for a variety of reasons including illness or maternity leave. Examination rooms were consistently small, with few doors and limited privacy. Several ultrasound exam rooms (see Figure 2) have curtains to dim the room sufficiently to review ultrasound images.

In the clinics we visited, the clinical exam room (where intake and patient history occur) is separate from the scanning room, which may be on the other side of the clinic. The U/S device used by midwives is theoretically portable, but it is kept in a locked room for which only midwives determined to have U/S expertise have keys. Because the U/S machine is in a separate room, midwives are required to change locations halfway through a prenatal exam to use the device. When many patients are waiting and the current patient appears to have a normal pregnancy, moving locations to conduct the exam can be a disincentive to use U/S. Co-locating the device in the same room as other exam activities may encourage usage.

Midwives universally indicated that their patient load was consistently high, and highest on village market days; since patients would already be traveling that day, they often came to the clinic as well. At no time did midwives lack patients; one midwife reported that patients often slept outside the clinic to receive prenatal care. The number of babies delivered at the clinics ranged from 30 per month at the smallest clinic to 150 per month at the largest clinic.

Competing Responsibilities

One midwife, Sarah, considered herself a "small doctor," and actively encouraged her distributed midwife peers to do the same. Sarah endeavored to "stand on [her] own two feet" and have sufficient skills to provide each patient with coordinated, comprehensive care and treatment. In addition to using U/S to screen women for high-risk pregnancy conditions, midwives' other responsibilities include patient education and communication, delivering babies, and providing other types of care, including vaccination.

Midwives at clinics leverage the healthcare system's referral network, meaning more severe cases (e.g. high-risk pregnancies) are referred to higher-level health clinics equipped to deal with these contingencies. The referral system requires midwives to engage in articulation work to coordinate and monitor transfer of patients from one clinic to another. For example, midwives at clinics spend significant time reporting clinical findings and actions taken for each patient seen. If a case is particularly high-risk and urgent, they may call midwives at a higher-level clinic to alert them that the referred patient is on her way. Additional actors, such as ambulance drivers, also participate in coordinating and scheduling activities.

Technological Ecosystem

The technological ecosystem at each clinic varied, though there were common themes. Reliable power sources were mostly non-existent. Several clinics addressed the lack of infrastructure with solar panels. One clinic reported broken solar panels, and midwives told of delivering babies in the middle of the night by kerosene lamp.

Mobile devices were widespread. All midwives had basic cell phones; most had multiple phones for different providers with prepaid airtime. Throughout 2010-2011, our research team noted a lack of consistent cell service in the district. Clinics varied in the provider who had the most reliable service for that area, and even traveling 5-10 km could mean a new provider was needed in order to make a call. Functional Internet connectivity was non-existent in the clinics. GPRS modems provided some limited connectivity, though, as noted, cell service was sparse. In the villages, some residents had satellite televisions and would charge neighbors to watch programs on certain evenings. One midwife had a digital camera which she used to take photographs of us and mentioned that she would upload them to the Internet in Mbarara.

Remote Training Opportunities & Motivations

For all of the midwives interviewed, the only opportunities for continued education were in Mbarara, or Kampala, larger cities that are one and six hours away, respectively. For all midwives, it was difficult to travel to these cities for additional training, both because of the high cost of travel and because if they left, they would be leaving the only other midwife at the clinic alone for several weeks. One midwife, Faridah, said she only receives continuing education through the local sonographer when problems arise. Another midwife, Sarah, was much more proactive about receiving continuing education. She would often travel to Mbarara to access the Internet, which she used to keep abreast of best practices by emailing with various professionals she had met.

All midwives interviewed expressed a desire to learn more about midwifery, U/S, and medicine more generally. One midwife, Namutebi, expressed interest in our system's integrated help feature simply as an educational replacement for her textbooks, which she realized were extremely dated. When showed a prototype of our integrated help system, all midwives recognized in it the potential to assist with continuing education and help them remember what to do when faced with unusual medical conditions. One midwife stated, "if you are having trouble with the head circumference you can look at the text, and then you can measure the head circumference immediately." Another midwife asked if we could put our help system into the devices they are currently using, so they could begin accessing the information immediately.

Radiological Practice in the United States

Below is an aggregate example based on our interviews with sonographers, physicians, and radiologists in June 2011 that provides a scenario for radiological practice in a high resource environment:

A family practice doctor sees a patient, and, based on the initial exam, orders up an imaging test such as U/S. A radiologist receives what is known then as the referral. The radiologist may have questions for the family doctor, known as the referring doctor, based on the kind of imaging that was requested, in which case she or he will pick up the phone or walk down the hall, depending on the work setting. Once those issues have been clarified and the right tests decided on, the imaging is performed by a technician. The results are delivered electronically to the radiologist via PACS. At that point, the radiologist may have other questions about patient history and need more information in order to interpret the test results accurately. In order to do this, the radiologist will contact the referring physician (via phone, face-to-face, or e-mail), or even go visit the patient to acquire that information. In some cases, the radiologist will confer with other radiological colleagues for help making sense of an unusual test result. The family practice doctor receives the results and seeks out the radiologist for clarification or to discuss specific elements in the image. Both the family physician and the radiologist can look at the screen together, or they can talk on the phone while both look at the images using PACS. The referring physician makes patient care decisions based on the negotiated understanding of the test results.

This scenario demonstrates the intensely collaborative practice within which the clinical use of imaging technology is situated. This contrasts sharply with the picture of the remote practitioner that we see in Uganda. The technological infrastructure that supports this collaboration is also starkly different.

Solitary vs. Collaborative Practice

All radiologists, primary care physicians, and sonographers in Seattle reported that patient care is delivered by teams of practitioners, and that radiological practice, in particular, is performed and interpreted as part of a team process. As a reminder, we included these three types of U/S consumers because midwives in Uganda perform work that spans all three specialties, from selecting U/S as a diagnostic tool, to conducting the U/S exam, to interpreting the results.

Reliance on PACS

The collaboration described above predates computer technology; three decades ago radiologists and referring physicians would meet in the reading room and read films against a light wall. That collaborative practice today is mediated by PACS. All doctors interviewed indicated that they used PACS to read and annotate images, communicate diagnoses, and create an ongoing patient record. There are multiple versions of PACS, most are proprietary, and interoperability can be an issue across different systems. PACS was characterized by some respondents as complex and by others as intuitive; PACS systems are chosen by hospital administrations rather than individual practitioners, and they are adopted throughout the institution. PACS replaces darkened reading rooms where radiologists and other clinicians would consult while looking simultaneously at the films. PACS now allows for asynchronous collaboration, as radiologists and surgeons—or other clinicians—read, negotiate, and interpret U/S and other imaging test results. However, even though PACS seeks to make collaboration more efficient, it has not eliminated the need for synchronous consultations among radiologists and referring physicians, as described below.

The Work Environment

The work environment for all of our respondents—referring physicians, radiologists, and sonographers—is highly technological. They work with landlines, cellphones, pagers, networked computers, backup networks, automated voice recognition systems, multiple viewing stations, and email. Multiple screens are common (see Figure 2), as is computerized voice dictation that populates patient records. The reading room is still a dark place, primarily to improve image viewing on the screens.

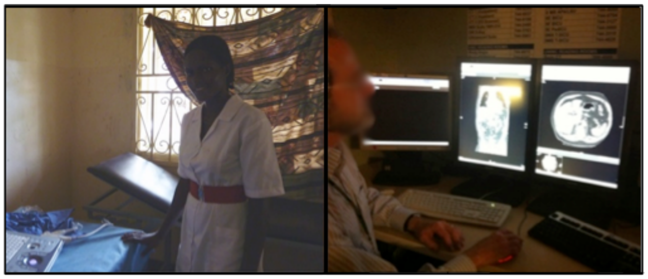

Figure 2: Contrasting settings in which practitioners view ultrasound images: Ugandan Ultrasound Exam Room (left) and United States Radiological Viewing Room (right)

In the hospital setting where we conducted our research, which is a teaching hospital, the Fellow on shift reviews the work of the residents and consults with the attending physician as necessary. When attending physicians begin their shift, they start by reviewing the work done overnight by the residents, checking notes and diagnoses. When there are questions, the attending physician will walk over to discuss the images and interpretations with the Fellow or the residents. This teaching relationship provides realtime and ongoing learning opportunities, and later in this paper we discuss the importance this collaborative practice plays in the effective use of imaging.

Networked and In-Person Collaboration

Imaging reports stored in PACS can be used in both synchronous and asynchronous communicative contexts. In some clinical settings, clinicians are able to review images face-to-face with their radiology colleagues in viewing rooms. When this is not possible, reports serve as an asynchronous "shared text"—radiologists leave written or dictated notes and annotations alongside images which the clinician reviews and, based on that reading, then contacts the radiologist by phone for further consultation if necessary. The radiologists, in particular, reported using the phone heavily, with one doctor using the phone for 15 or 20 cases in a day when working an emergency room shift. The same doctor reported that when doing a significant amount of outpatient work—that is, reading the results of tests where the referral doctors are offsite, he used the phone up to a half dozen times a day. He said the phone was most often useful as a supplemental medium for complex cases, which generally meant more acute cases.

All of our interviewed physicians emphasized the importance of combining the knowledge and expertise of the radiologist and the referring physician, sometimes supplementing this information by walking over and observing the patient in order to help accurately interpret the films. As one interviewed physician stated, "I've been doing this a long time, and I know a lot of medicine, but I can only use that if I have a lot of history. So on complicated cases I want a lot of [patient] history."

In the United States, clinicians are able to consult with radiologists over the phone about images stored in networked PACS. Radiologists direct clinicians to various anatomical structures found within the images, and towards an ultimate diagnosis, using shared medical vocabulary. Although clinicians do not have the same depth of radiological vocabulary as radiologists, participants agreed there is sufficient shared medical vocabulary to explain findings. According to one primary care clinician, the purpose of reviewing the images with a radiologist—as opposed to the radiologist merely communicating the final diagnosis—was to continue to educate herself, and also to be able to describe findings to her patients.

Overall, substantial collaboration between the radiologist and the sonographer is necessary. As one radiologist reported, "U/S is [about] hands-on interaction, so you can look at images, and you can interpret [those images], but you have no idea what *wasn't* seen by the sonographer. There [can be] a loss of quality, because you can't look at the cases [when you don't do the scanning yourself]." Additionally, using collaborative, distributed practices with U/S can introduce complications that are specific to the technology. As one sonographer reported, U/S is different from other imaging modalities because the real time scan (with video) provides a "different scenario" than looking at still images after an exam. She "lose[s] a significant amount of understanding with still images," which makes it especially important that PACS allows upload of both images and video.

Opportunities for Consultation and Learning

All of the practitioners interviewed mentioned a variety of tools and methods they use to ensure ongoing medical learning and alliance with current best practices. These knowledge exchanges were both technologically mediated (e.g. through e-mail), mediated through more traditional mediums (e.g. handwritten notes), or unmediated (e.g. in-person communication or seminars).

Several participants mentioned reliance on medical information databases paid for by their respective hospitals, including UpToDate [32] and MD Consult [22]. Both services offer peer reviewed medical information and are available both online and offline. Participants mentioned that they use these resources to discover new treatment options and assist with patient education efforts.

One clinician with experience working in rural medicine mentioned reliance on MEDCON—a toll-free phone consultation and referral service for clinicians in Washington, Wyoming, Alaska, Montana and Idaho [21]. The participant described the importance of this service to remote referring physicians, who may not have a large network of colleagues to consult with in person. All of our participants emphasized the importance of being able to ask colleagues for help in person or over the phone. One sonographer mentioned that if she encountered something she was unsure of with a particular scan, she may ask a sonographer colleague to come into the exam room and scan the patient in order to provide a second opinion. This is not possible for remote practitioners, and in these cases, phone consultation would be even more important.

An additional challenge associated with networked collaboration for U/S relates to specific technical challenges. As one radiologist noted, "technical issues obviously [bear on the quality of test results]—speed, archiving, etc. In a practical sense, measurements you want but weren't taken are out. Brightness, contract, etc. adjustments are also out [when the scanning is done by a different person or at a different site]." While this radiologist said these were mostly solvable problems, in places with intermittent and unreliable connectivity where the sharing of images and information may be sporadic or expensive, such gaps can become especially important.

Also related to technical issues with U/S, "one other issue that is a big thing is that you're not involved in protocoling or [selecting] the type of equipment the case is done on. [It can be a problem] if you're not there to make sure things are done correctly. Lots of studies are not done quite right, so you need to repeat studies from a remote clinician." Such problems weren't as marked for imaging technologies like CT or MRIs, but for U/S these problems were notable. This is especially relevant for projects that seek to introduce U/S to remote or low-resource settings for local scans and depend on sending those images to developed world radiologists for interpretation.

Many of our participants described scenarios that highlighted the importance of trust in relationships between imaging specialists and referring physicians. As one sonographer mentioned, "Doctors like to get the feedback from the source. That's the importance of real time…Sonographers are there in the room with the images—they [referring physicians] trust us. Trust goes a long way." Because referring physicians are not in the room with patients during the scan and often lack the image interpretation skills required by U/S, they place their trust in radiologists and sonographers with whom they often have an established working relationship. One family medicine doctor with twelve years of experience said, "I trust the opinions of radiologists who are really good at clinical correlation…If I have worked with them for a long time, if they are usually right, I will ask 'By the literature, or by your experience, what's the prognosis?'"

DISCUSSION

Hidden Work Practices and Collaboration

A major difference between high-resource and low-resource radiological environment is the extent of collaboration. In high resource environments where health settings separate expertise into different practitioners, there also happens to be robust enough technological infrastructure to support collaboration. We would argue that coupling multiple practitioners with a sophisticated technological ecology is a pervasive expectation for U/S usage and constitutes an important hidden work practice.

Our interviews with practicing clinicians in the developed world indicate that much of the complexity surrounding radiological practice is managed through comprehensive and multi-layered collaboration. The efficiencies of PACS do not remove the necessity of ongoing cooperation among different clinicians. PACS also does not eliminate the need for strong trust relationships between clinicians.

Access to Expertise

Several US-based participants identified lack of either in person or technologically-mediated resources that can deliver best practices as the central challenge facing isolated/remote practitioners. As one doctor with rural medicine experience explained, "You're isolated in space, but you really do need access to experts." This finding is corroborated by the teaching relationship between radiologists and their residents; initially, radiologists guide the residents through past cases, primarily to ensure they understand why each study was requested. Over time, residents shift into a more autonomous role and radiologists spend less time checking for errors.

Importance of Technological Ecology

There are, in fact, an increasing number of commercial U/S systems targeted at the low-resource market. Small-scale and low-power devices are becoming common (e.g. GE V-Scan and Mobisante). However, as our research has shown, a smaller, cheaper, easier to use, or more portable U/S machine isn't all that is required for effective U/S implementation. Understanding the work context in which U/S is deployed makes it clear that the larger technology ecology has some bearing on the effectiveness of the device. Importantly, no low-cost U/S project to date has focused on how work practices interplay with technologies to create work outcomes.

As one of the radiologists we interviewed noted, missing context from an examination is one of the biggest obstacles in teleradiology. Video clips are one way to alleviate the problem of missing context, and many U/S systems provide a mechanism for recording video. Additionally, many commercial systems, which are comprised of integrated devices, offer a way to send images and video clips through the Internet. However, many areas in the developing world have limited (or no) Internet connectivity. Even GPRS for sending data over mobile networks can be severely limited or prohibitively expensive. Further, where Internet connectivity does exist, bandwidth is so limited that video clips cannot be sent in a reasonable time frame. Because our device is a simple tablet device, video clips and images can be transferred in a number of ways, including through saving files onto a USB drive.

Future Design Considerations

The findings from this study emphasize differences between work settings and practices across our research sites. For our work with the Ugandan midwives, we would hypothesize that U/S can work adequately in their clinics because their work practice currently requires them to be solitary practitioners who work alone and operate as sonographer, primary care physician, and radiologist all at once. Thus, there is no need for them to collaborate and share imaging results and interpretations with other practitioners, so the lack of robust technological infrastructure doesn't limit them. However, we foresee problems in a scenario when midwives send patients to referral hospitals and then introduce a collaborative work practice that spans rural clinic and hospital without a technological ecology to support collaboration between the sites. Additionally, we hypothesize that the introduction of U/S into more complex healthcare settings with specialized health practitioners but that lack technological infrastructure to support effective CSCW practices among those specialists would have difficulty effectively incorporating imaging technologies into their practice.

Indeed, our research indicates that U/S in single practitioner settings can work without a large technical infrastructure, in part because the real-time nature of the modality means that the sonographer has enough contextual information from being present at the time of scan in order to make her diagnosis. Despite the advantage of context provided by being present at the time of scan, however, U/S images are often ambiguous, and our design strategies need to address this issue. Our interviews with sonographers indicate that learning from other practitioners—both as a novice and an expert—is crucial, and our project needs to consider this in future work as we aim to better support remote practitioners. Our integrated Help system is an attempt at solving this problem. Additional design considerations for us, and the wider field, to consider include:

1) Imaging technologies designed for complex, cooperative health care in Western settings are unlikely to be successfully adapted for remote practitioners. Rural clinics do not have the resources or network infrastructure to collaborate through computer technologies. In addition, the resource-constrained health professional must assume multiple roles (e.g., patient consultation, performing scans, etc), reducing the need for a complex collaboration system.

2) Trust in the expertise of one's collaborators is important when scanning and reading are separated. If practitioners are separated geographically and/or culturally, how difficult will it be to establish trusted relationships between those who scan and those who read?

3) Because health practitioners in remote settings lack access to a variety of resources, system design must compensate for lack of infrastructure in natural and innovative ways. The Ultrasound PLUS help system enables midwives to access reference and support in lieu of in-person and technically supported collaborative networks.

4) While ICTD work has made great strides in understanding the interplay of technical and cultural issues, adding an understanding of CSCW issues and how work practices emerge out of available technical infrastructure will increase the likelihood that the rapidly growing field of low-cost healthcare technology development for low-resource settings will result in appropriate solutions. Even if it appears that minimal collaboration takes place (e.g. in the remote practitioner scenario), it still exists and, if recognized, can be better supported in the design of novel technologies.

CONCLUSION

The authors of this paper are a group of medical professionals, computer scientists, and social scientists committed to appropriate technology development that can solve problems in low-resource environments. This paper was motivated by an understanding that the field of CSCW provides insight into work practices, including hidden work and socio-organizational issues, that are crucial to any successful technology development project geared for professional settings. Our findings in this paper have provided a clear framework for moving forward in our design efforts for the Ultrasound PLUS, but they have also provided some beginning guidelines for technology development efforts for low-resource communities that hope to target collaborative workplace practices and creatively compensate for gaps in infrastructure.

ACKNOWLEDGMENTS

Thank you to Gaetano Borriello, Nicole Goldsmith, Leo Ham, Matthew Hicks, Pratik Prasad, Ginger Ruddy, Laura Schlenke. Also to William Richard and David Zar for their contributions to the ultrasound technology field. We thank Michael Kawooya and his colleagues at ECUREI. Finally, we thank our study participants. This work was supported by a grant from the Bill & Melinda Gates Foundation's Grand Challenges Explorations Initiative.

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