MENDING THE GAP: A RESOURCEFUL SOLUTION FOR MEDICAL EQUIPMENT MANAGEMENT DISPARITY

BY

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LIST OF ABBREVIATIONS

AIC – African Inland Church

Biomed – Biomedical Engineering Department

DICOM – Digital Imaging and Communications in Medicine

GNI – Gross National Income

ICU – Intensive Care Unit

KH – AIC Kijabe Hospital

KSH – Kenyan Shilling

MENDS – Medical Equipment Network Documentation System

OPD – Outpatient Department

PACS – Picture Archiving and Communication System

SMS API – Short Message Service Application Programming Interface

UN – United Nations

WFBMC – Wake Forest Baptist Medical Center

WFSOM – Wake Forest School of Medicine

WHO – World Health Organization

ABSTRACT

Developing countries rely heavily on donated medical equipment from high income countries, which often challenges their limited resources, just to provide necessary and common medical attention. A team from Wake Forest Baptist Medical Center confirmed this situation during a two-week intensive investigation at AIC Kijabe Hospital in Kijabe, Kenya, who experience an average of over 10,000 reported issues each year, often leaving equipment to sit unused. Currently there is a gap in the communication network of maintenance and management systems at resource-limited facilities, like AIC Kijabe Hospital, hindering the monitoring and timely repair of medical equipment to help sustain good medical care. Our goal is to create a more comprehensive and organized record of equipment services, thereby improving communication and responsiveness. The Medical Equipment Network Documentation System (MENDS) provides a simple communication network for equipment servicing from failure to restoration using text messaging.

MENDS was created to provide an automated system that captures and documents information about requests and repairs of medical equipment. Information relative to the content of MENDS was collected from AIC Kijabe Hospital. A preliminary test completed at Wake Forest Baptist Medical Center confirmed the functionality and usability of MENDS. MENDS was then deployed in Kijabe, Kenya for a three-month pilot test. The results show MENDS more than doubles documentation and enhances ease and speed of communication. Comprehensive data MENDS provided created more accurate measures of equipment performance, which can be used to improve turnaround time, efficiency of repairs, equipment quality, and procurement.

Chapter I: Background and Introduction

GLOBAL HEALTH

The United Nations (UN) has divided the world into three categories – developed, developing, and least developed countries [1]. Developed and developing countries are mainly categorized based on gross national income (GNI), but there are no set universal criteria. Developed countries are known to have diversified economies relying heavily on technology, and typically enjoy high standards of living. Developing countries have underdeveloped infrastructures and a low human development index – a measurement of life expectancy, education, and standard of living [2]. Least developed countries however, are categorized as having a low national income of less than $900 per capita gross domestic product and are considered economically vulnerable [2]. As of 2018, least developed countries include, but are not limited to Haiti, Cambodia, Rwanda, and Uganda [3]. Developing countries include Jamaica, Iraq, Kenya, and Algeria, and developed countries include the United States, Japan, the United Kingdom, and Belgium, among many others [4].

It is mainly economic conditions that define these states of development, which pours into the vast differences in healthcare among regions. Many infectious diseases like Tuberculosis and Malaria run rampant in developing countries because of the poverty, poor infrastructure, and a severe lack in healthcare resources [2]. Such difficulties contribute to the short lifespan and low quality of life for the citizens. The average life expectancy in Kenya is about 65 years while in the United States it is nearly 80 [5]. Many health care professionals in developed countries have shifted to the area of Global Health in order to prioritize the improvement of health in underdeveloped regions to achieve health equity for all people [6].

RESOURCE-POOR FACILITIES

About 80% of the world's population reside is developing countries, yet most recent medical technology advances are only available to a small portion of the world [2]. The top 30 health technology companies which account for 89% of sales revenue have their headquarters in developed countries [7]. This includes Medtronic, Abbott Laboratories, Stryker Corporation, and General Electric. But even within developed countries these advanced technologies raise a cost concern. On average the annual health expenditure is more than $1800 per person in developed countries, while in least developed countries it is about $16 per person [2].

Within developing countries there are private, government, and charity medical facilities, and much of the technology is concentrated in the private sector. These private facilities usually provide exceptional care, but only serve a small portion of the population, about 4%, and patients in these facilities are required to pay full service fees. Most of the population visits charity or government hospitals because they are only required to pay a small copay while receiving the remainder of the financial support elsewhere, either governmental or foreign [8]. At charity and mission facilities, the costs are subsidized by affiliate churches or directly from the government in that country. Government facilities are mainly funded by general tax revenue [9]. Cost is a major barrier not only in receiving standard practice medical care, but also in obtaining health care technology. Much of the larger equipment, like X-ray and CT scanners, can cost millions of dollars per unit and are rarely locally sourced [10]. But even smaller consumables can bare a large financial burden. The constant need to supply single-use gloves and test stripes is often underfunded to accommodate other product needs, and results in supply deficiencies slowing productivity and hindering proper services [8].

Developed nations, such as China, Japan, the United States and several countries in Europe attempt to bridge the gap by providing access to necessary healthcare in the form of equipment donations [11]. The stakeholders involved in the donation process mainly include local nongovernmental organizations, health ministries, churches, and international civic organizations. Unfortunately, donors do not have much knowledge about the landscape and needs of the facilities, so they are not able to maximize the impact. As a result, and without intention, the donated equipment can cause an array of unforeseen difficulties. [12]. The World Health Organization (WHO) offers certain guidelines for the donor and recipient to help create a successful donation. However, these guidelines are often not enforced and are also left to one’s own interpretation. WHO advises that:

1. Donations should benefit the recipient to the maximum extent possible.
2. Donations should be given with respect and in conformity with government and administrative arrangements of the recipient.
3. There should be no double standard in quality.
4. There should be effective communication between donor and recipient [13].

There are often complications with the donated equipment that ultimately lead to service outages. Table 1 shows the percentage of out of service equipment by country in 16 different countries. The data comprises inventory ranging from 1986 to 2010 with

96% of the equipment in the survey originating from developing countries. The data depicts that about 40% of the surveyed equipment was out of service [11].

Table 1: Data showing percentage of out of service equipment in 16 surveyed countries[11]

Year	**Country**	**Total pieces**	**# Out of service**	**Percent out of service (%)**
1986	Belize	50	20	40.00
1986	Costa Rica	962	8	0.83
1986	El Salvador	1,384	353	25.51
1986	Guatemala	931	165	17.72
1986	Honduras	785	122	15.54
1986	Nicaragua	1,065	310	29.11
1986	Panama	829	59	7.12
1987	Bolivia	3,296	1,335	40.50
1987	Colombia	14,962	6,817	45.56
1987	Ecuador	3,405	1,390	40.82
1987	Peru	4,253	1,844	43.36
1987	Venezuela	6,527	3,068	47.00
1991	Nigeria	2,199	674	30.65
2005	Indonesia	2,365	428	18.10
2008	Ethiopia	65,668	25,610	39.00
2010	Cambodia	3,359	722	21.49
Total		112,040	42,925	38.31

Medical equipment can be in a state of unused or out of service in developing countries for a number of reasons. The reasons include:

1. Infrastructure and resources [11].
    a. Equipment donated from other countries leave very little local availability of spare parts or required accessories. Therefore, when making repairs, the facilities must reach out to the original manufacturer in foreign countries requesting parts to be sent. The process quickly becomes expensive and time consuming due to

international shipping. While the hospital waits to purchase and receive the parts, the equipment is left to sit unused which in turn creates a strain on patient care.

   b. There are occasions when the equipment is simply unusable. Equipment may have reached end-of-life, the voltage capacity differs from what is available, or repair costs exceed the equipment value.
   c. Disposal of medical equipment can be costly due to environmental or patient information concerns. If there is not already a procedure for disposal in place, the equipment can quickly become a burden to the facility.
   d. Additional issues may include that the equipment received is faulty or they may already have a surplus of it [12]. Developing countries are limited by the economic infrastructure including transportation, health, environmental, and energy which reduces the capacity for obtaining and maintaining reliable foreign resources.
2. Health technology management [11].
   a. Inconsistent equipment management at the facilities can lead to prolonged unusable equipment. Two examples are the failure to report equipment issues and performing regular preventative maintenance. When issues or breakdowns are not properly reported in a timely manner, repairs are delayed and equipment is unused which impedes continued medical care. Preventative maintenance is essential to the upkeep of equipment. It helps to avoid possible breakdowns and

decreases the rate of equipment deterioration. The longevity of medical technology is highly dependent on the proper management and requires a coherent system and protocol.

   b. Management will make purchasing decisions without consulting the technical or engineering team. The repercussions may include, purchasing incorrect parts and quantities which leads to repurchasing orders increasing the cost and extending procurement time and duration of out of commission equipment.

3. Training of personnel [11].
   a. The donated equipment at the facilities cover a wide variety of brands, manufacturers, and ages, which complicate the repair process. The technicians responsible for their maintenance are often not trained on the use and function of the equipment and may not have access to the manual. Overtime they learn how to maintain the equipment, but the variety of equipment makes it nearly impossible to become an expert on all repairs.
   b. The doctors and nurses are tasked with learning how to use the equipment on the job. With a lack of user manuals this results in a great deal of user error. Even simple mistakes can cause a delay in treatment as they try to figure out the issue themselves or wait for a technician to come solve the problem.

The failed or out of service equipment bares a significant financial impact on the facility depending on the repair needs. Equipment with a mean time to repair of four days or less can create an economic loss of $500 to $2000. Equipment that needs attention from external resources, such as a technician directly from the manufacturing company, can create an economic loss of $2000 to $5000. When a device is no longer usable and a new device needs to be obtained, it can create an economic loss of greater than $5000 [14]. These costs are from a single failed device and will increase as more equipment breaks down.

CURRENT TECHNIQUES

Developing countries have to contend with a plethora of problems when using donated equipment. As a result, the current trend is to embrace the idea of frugal technology rather than combat all the issues from using donated equipment. Frugal technology is cost effective and developed specifically to accommodate for the local conditions [7]. Organization like Engineering World Health, are dedicated to delivering appropriate health care technology to developing countries. They wish to gain insight as to why equipment fails in order to design devices that are better suited for the setting [8].

Like many medical professionals in developing countries who practice improvised medicine in order to create results with the tools they already have [15], equipment technicians improvise when called upon to make repairs. Without the conventional proper resources needed to perform certain treatments or services, caregivers and technicians improvise and devise a solution using materials they have on hand.

OBJECTIVE

This study aims to identify a pressing need in resource-poor medical settings relative to medical equipment and processes. Once the need is identified, our goal is to develop a low cost, sustainable solution and implement it in a resource-limited medical facility. The objective is to evaluate the developed solution and draw conclusions as to its ability to meet the need, its effect on the healthcare of that facility, and its compatibility with the environment.

CHAPTER SUMMARIES

Chapter II: Assessment of Medical Process and Equipment Needs in Rural and Remote Developing Countries

Performed an onsite investigation of needs in a resource-poor medical facility pertaining to medical devices and various procedures. Also, evaluated the needs in order to focus on one particular need for which a solution can be accomplished.

Chapter III: Mobile Documentation System for Medical Equipment Servicing in Developing Countries

A description of the development of a mobile system for tracking and documenting equipment services. A preliminary test of the system is conducted and evaluated in which the results are discussed.

Chapter IV: Implementation of an Automated Medical Equipment Management System for Resource Limited Settings

An in country pilot test of the mobile system and its evaluation against the current method of communication and documentation.

Chapter V: Summary of Research

A summarization of all the research presented in this thesis.

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Chapter II: Assessment of Medical Processes and Equipment Needs in Rural and Remote Developing Countries

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ABSTRACT

A team from Wake Forest Baptist Medical Center – Rayonna Gordon and Evelyn Anthony – traveled to AIC Kijabe Hospital in Kijabe, Kenya to obtain insight and embed with a team of staff engineers to observe medical process issues, equipment issues, and the contributing environmental factors faced at the hospital. The visit confirmed published research of conditions in resource-limited facilities. The objective of this study is to identify a single medical device or process need at AIC Kijabe Hospital for which a solution can be developed over a two-year period to improve health outcomes at the hospital and other resource-poor facilities with similar needs. Information was gathered using three methods: observing the hospital's Biomedical Engineering team as they worked on the medical equipment, watching actual medical procedures conducted in the hospital, and interviewing various personnel in order to record in depth accounts of concerning needs, opinions, and thought processes. A list of issues and needs observed and discussed was compiled for further evaluation.

The compiled issues and needs were placed in a decision matrix and scored based on the following criteria; frequency of issue, feasibility, interest, and affordability. The top three scoring needs/issues were Store Ultrasound Images to PACS – total score of 14, Equipment User Error – total score of 15, Documentation – total score of 16. After in depth research into the root cause of each of the top three issues, it was determined that, within the time constraint, an improved documentation system is the most feasible focus for a valuable impact at AIC Kijabe Hospital. We seek to achieve a durable and dependable means for documenting data in order to develop a system that can be managed in the developing world.

INTRODUCTION

A literature search was conducted to reveal possible medical device and procedure related needs in the world's impoverished and resource-limited regions. Travel plans were organized in order to make firsthand examinations in the setting of interest. A current relationship between Wake Forest University School of Medicine (WFSOM) and AIC Kijabe Hospital (KH) in Kijabe, Kenya was leveraged to complete the study. This partnership, in which medical students, residents, and other professionals conduct research and donate their services; was an ideal setting for the research [1]. The purpose of the onsite investigation was to obtain insight and embed within the Biomedical Engineering Department (Biomed) at KH to observe medical process issues, equipment issues, and the contributing environmental factors at KH.

Research Study Setting and Background Information

Kenya is located on the eastern coast of Africa bordering the Indian Ocean. It is the 50th largest country in the world by area. The official languages of Kenya are English and Swahili [2]. As of 2018, Kenya has a population of over 48 million people. The United Nations (UN) quantifies Kenya's remoteness by measuring how far the country is from reaching a significant fraction of the world's market. Kenya has a remoteness rating of 55.5 while its neighboring least developed countries, such as Uganda and South Soudan, are rated at 68 and 64 respectively. Twenty-two percent of Kenya's total population 15 years of age and older are illiterate.

The gross national income (GNI) is about $1300 per capita [3]. Kenya's economic development has been stunted by weak government and corruption. Unemployment reaches almost 40% of the population. Agriculture and livestock are a major source of

Kenya's economy including products such as tea, coffee, sugarcane, beef, and poultry. A secondary source for the economy is tourism. A large number of products are imported including oil, iron, steel, vehicles and other machinery. Thirteen million people in Kenya are without electricity and only about 26% of the population use the internet. Despite the relatively low levels of economic development, 97 out of every 100 people have mobile phones [2]. This fact was viewed by the team as an important area of focus since the technology was readily available.

Kijabe is located about 40 miles north of Nairobi, the capital city of Kenya, and 7200 feet above sea level. Kijabe translates to "Place of Winds" because of its windy climate. The weather is typically around 75 degrees Fahrenheit in the day and drops to about 55 degrees Fahrenheit at night. Kijabe experiences two rainy seasons, March to June and October to December. The remainder of the year is relatively dry.

KH is a non-profit mission hospital operated by African Inland Church (AIC) [4]. The hospital was established in 1915 as a small outpatient clinic and the present complex opened in 1961 [5], [4]. It currently holds 340 beds with a number of inpatient and outpatient services including operating rooms, 24-hour emergency department, ear, nose, and throat department, and a dental facility. Bed occupancy currently averages at 80%. KH provides pathology services to over 30 hospitals across East Africa and mobile health teams are sent to surrounding villages each month to provide services [4]. KH has three satellite clinics located in Nairobi, Marira, and Naivasha [5]. The hospital also provides training for nurses and medical students from multiple countries, and has evangelism and chaplaincy programs [4]. According to the medical board of Kenya, KH is a level 6B (out of 6 levels) National Tertiary Referral and Teaching Hospital [5].

The objective of this study is to identify a single medical device or process need at KH, with applications in other similar healthcare settings, for which a solution can be developed over a two-year period. The goal is to improve health outcomes at KH and other resource-poor facilities with similar needs.

METHODS AND MATERIALS

A team of WFSOM students and professionals led by Dr. Evelyn Anthony traveled to Kenya on December 28, 2018. The onsite travel and lodging was coordinated by World Medical Mission - Samaritan’s Purse, an organization responsible for placing volunteer Christian medical personnel at medical facilities around the world [4]. The team traveled from Nairobi to Kijabe and stayed on-site at the KH complex for two weeks. The team was given a tour of the hospital and introduced to our respective departments in which we would be working for the entirety of our stay. The research presented in this thesis was conducted with the biomed department. The data collection was gathered while shadowing the engineers as they serviced the medical equipment within the hospital. There were a total of four engineers employed, however one was on leave for the month, and therefore only three engineers were working during the investigation period.

Information was gathered by watching actual medical procedures, interviewing personnel in order to record in depth accounts of concerning needs, opinions, and thought processes, and observing the engineers as they worked. Table 2 shows the template used to evaluate observed medical procedures.

Table 2: Template to record observations of procedures

Procedural Observation
Date: ____________ Time: ______ Location: _________________
Who is present? (roles and specialties, names if possible)
Environmental Factors (smell, temperature, sight)
Type of procedure and total length of time
Preparation for procedure
Steps of procedure (length of time for each step)
Devices used in procedure and how they are being used (include drawings if needed)
Specific words and phrases used (*indicates unfamiliar terms)
Behavior and when behavior was expressed (i.e. frustration, excitement)
Difficulties expressed or observed (device related, patient related, etc.)
Questions and Comments

The following medical procedures were observed and observation notes and images of these procedures can be found in Appendix A:

- Baby resuscitation
- Caesarean section
- CT scan
- Endoscopy procedure
- Tooth extraction

Table 3 shows initial interview questions asked of various hospital personnel.

Table 3: Interview questions for individuals involved in the medical process

<table>
<tr><td colspan="2">Interview Questions:</td></tr>
<tr><td>Patient</td><td>Engineers</td></tr>
<tr><td>
• What preparation did you need to take before the procedure?
• How was your experience getting to the hospital?
• How long was the wait? Was it comfortable?
• What do you like and dislike about the procedure? About the device?
• What is your pain/discomfort level? (before, during, after, and upon leaving)
• What improvements do you recommend?
• How long before you can resume normal activity?
</td><td>
• Type of equipment and its use?
• How frequently is it used?
• Where is it stored? Where is it when being used?
• What difficulties do you have with the equipment?
• Are repairs needed? Type of repairs? How often? How long does it take? Do you need replacement parts? How much do they cost?
• What is your weekly work schedule like?
• Describe a busy day in the hospital?
• Suggestions?
</td></tr>
<tr><td>Healthcare System</td><td>Providers (nurses, doctors, etc.)</td></tr>
<tr><td>
• What is the cost of device/equipment/supplies?
• What factors drive up the cost of procedures? Of equipment procurement?
• What resources are tied up during the procedure?
• What training or certificate programs are available?
</td><td>
• What is the staffing level structure?
• What is your role?
• Does the person have the same role throughout procedure?
• Were there any difficulties during procedure?
• Do the devices work as you desire?
• Were there any complications?
• What is the follow-up procedure? Length of time?
• Did you experience fatigue during procedure?
</td></tr>
</table>

Individuals in the following departments were interviewed:

- Biomed
- Electrical
- Simulation Laboratory
- Casualties (Emergency Room)
- Intensive Care Unit (ICU)

- Inpatient Wards (Men's and Private)
- Purchasing Office
- Theatre (Operating Room)
- Radiology
- Pediatrics
- Pathology

Observations were made of the engineers conducting maintenance on several pieces of equipment including surgical lights, suction, ventilators, and patient monitors. Figure 1 shows an engineer repairing the light fixture in the endoscopy room prior to a procedure and performing maintenance of a ventilator in the Theatre.

Figure 1: A) Engineer repairing light fixture in endoscopy room B) Engineer repairing bellows of ventilator in Theatre

Information about various equipment in the hospital was gathered, getting a description of what it does and any issues that it faces. Images and descriptions can be found in Appendix B.

Table 4 is a list of all issues and needs discussed and observed during the two-week period.

Table 4: List of issues and needs observed and discussed at Kijabe Hospital

Communication and Organization	Medical Procedure and Equipment

• Engineering not consulted on purchases
• Users don't take good care of equipment – user error *
• No permanent radiologist
• Unprepared to receive patients for operations
• Not enough supplies *
• Documentation
    o Many repair requests undocumented
    o Specifics on donations aren't passed through from missionary organizations
    o Unfinished order request to purchasing office
• Technician Training
    o Small working space
    o Self-training (online sources) inefficient
    o Collaboration with neighboring hospitals is mostly over the phone
    o Unknowledgeable about some equipment
• International purchasing *
    o Middle man companies in Kenya
    o Equipment requires different voltage – users may be unaware and use the wrong cord
	• Suction blockage on multiple machines *
	• EKG machine malfunction
	• Patient monitors reading errors *
	• Stiff bed rails
	• Food obstruction during endoscopy
	• Strenuous tooth extraction
	• Dental chair motion
	• Upgrading electrical system with new equipment
	• Spare Parts *
	    o Incompatibility with machine due to sources being different
	    o Difficulty finding because donated machines don't have documentation
	    o Take very long to come after ordering
	    o Difficult to find for older models because company stops making spares
	• Portable EEG machine/use less leads
	• Lack of water filter for Autoclave
	• Electric beds dysfunctional *
	• Heaters not working *
	• Ventilators break down *
	• Worn out blades on X-ray machine
	• X-ray not compatible with taller people
	• Only 1 cassette for iCRco, slows down process
	• Cassettes give poor quality (old)
	• Poor quality ultrasound images
	• Siemens Ultrasound doesn't save to PACS
	• Poor quality endoscopy image printer
	• Anesthesia machines break down
	• Breathing tubes on anesthesia machine detach
	• Need autostainer for pathology
	• Infrared malfunction for microtome

*Indicates an issue was discussed or observed more than once or by more than one person.

RESULTS

The team returned to the United States and analyzed the data collected. A decision matrix was created to determine which issue or need could be met within the two-year time frame. The criteria in the decision matrix included:

- Frequency of issue – the number of times the issue was observed or discussed. The number 1 denotes the issue was discussed/observed once, and the number 2 denotes it was discussed/observed more than once. The greatest impact can be made when finding a solution for a reoccurring issue.
- Feasibility – the likelihood of completing a solution by 2020. The likelihood was rated on a scale of 1-5; 1 being highly unlikely and 5 being highly likely. It was important that the team contribute a feasible solution within the allotted resources.
- Interest – the solution aligns with the training and expertise of the team. The interest was rated on a scale of 1-5; 1 denotes weakly aligns and 5 denotes strongly aligns. It is important that the team work within our interest for maximum benefit for both KH and the team.
- Affordability – the solution and development of the solution requires minimum funding while simultaneously having a significant impact. Affordability was rated on a scale of 1-5; 1 denotes highly unaffordable and 5 denotes highly affordable.

The above mentioned criteria were chosen because they strongly outline a path to successfully meet the goal of this study – to improve health outcomes at KH and other similar facilities.

The decision matrix placed the needs and issues into 29 categories and the discussed rating scale was used to score the categories. A category could receive a maximum total score of 17 and a minimum total score of 4. Total scores from the decision matrix is shown in Figure 2. The complete decision matrix is in Appendix C.

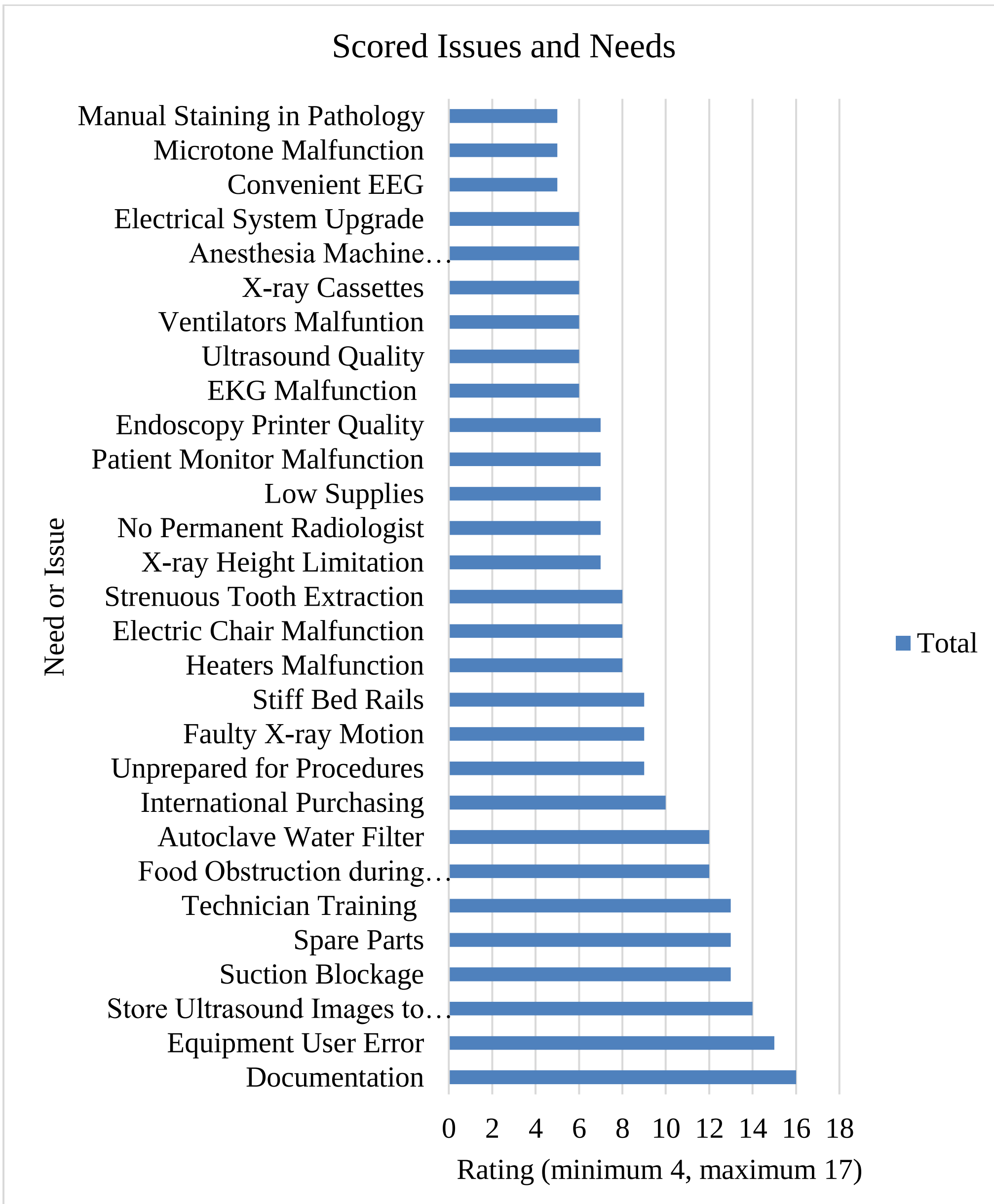

Figure 2: Total score in decision matrix for 29 needs observed and expressed at Kijabe Hospital

The top three categories shown in are: Store Ultrasound Images to PACS – total score of 14, Equipment User Error – total score of 15, Documentation – total score of 16.

Storing ultrasound images to PACS relates to one of the ultrasound machines inability to store digital images and reports onto the hospital's central Picture Archiving and Communication System (PACS). PACS allows medical professionals to access medical files from anywhere and eliminates the need for manual filing [6]. The inability to automatically store to PACS means the images either require a manual transfer from the ultrasound machine to a desktop computer, or the images are viewed on the ultrasound machine itself. However, due to the ultrasound machine having a finite storage space, images must subsequently be deleted once the memory reaches its capacity.

Equipment user error refers to the mistakes made by the equipment user that result in the failure of the equipment. It was commonly expressed that the equipment users simply did not take care of the equipment, and for this reason equipment malfunction was at an elevated rate.

Documentation refers to the inconsistencies in recordkeeping when obtaining services for the medical equipment in the hospital. The inconsistencies include:

1. Undocumented repair requests and reports.
2. Incomplete order request from departments to the purchasing office for parts and other supplies.
3. Neglecting to report specific information about equipment and donations from the missionary organizations to the key personnel.

DISCUSSION

Additional investigations were conducted on the top three scoring categories to ascertain the most viable focus for the study.

Further research was conducted on the issue of storing images to PACS. The issue was present only with KH's Siemens Acuson x300 Ultrasound which can be seen in Appendix B. The PACS system used for the hospital is ClearCanvas by Synaptive Medical (Toronto, Ontario, Canada). Multiple professionals in the medical imaging field were contacted as a research source. As a result, it was discovered a license for the DICOM 3.0 connectivity software through Siemens Healthineers (Erlangen, Germany) was needed for the Siemens ultrasound to push to ClearCanvas. DICOM, or Digital Imaging and Communications in Medicine, allows for the transmission, storage, and display of medical imaging information by properly formatting and exchanging [7]. DICOM 3.0 Connectivity would enable digital data transfer, connectivity to PACS, image printing, and exportation to DVD and CD.

The primary issue was that a DICOM 3.0 Connectivity license must be purchased and costs several thousand dollars or requires an annual fee. Ways to avoid purchasing the license were discussed by looking at current solutions to this problem. One solution was downloading images from the ultrasound to a USB and transferring them to a workstation computer that has ClearCanvas, then using a free software such as MIRC FileSender (Radiological Society of North America Teaching File System) to push to PACS. However, this is indirect and inconvenient. Another current solution is using a Capture Card. Capture Cards transfer real time images from the ultrasound to a desktop workstation. The Capture Card box is connected to the Ultrasound via HDMI or similar connection, then plugs into the workstation via USB. Once loaded onto the workstation computer, the images can be pushed to PACS. Though this solution is a bit more convenient it is still indirect.

Therefore, it was decided to direct focus on the possibility of a method to transfer images from the ultrasound machine to the workstation computer without the need for an external device. In depth research began and it was discovered there would be a need for internet access and/or additional hardware for successful transfer. Both internet access and additional hardware posed significant barriers in affordability, sustainability, and time sensitivity. As a result, storing ultrasound images to PACS was eliminated as a focus for the continuation of this study.

A deeper investigation was conducted to discover the root cause pertaining to equipment user error. The investigation uncovered multiple causes including:

1. Excessive user turnaround – Because KH is a mission and training facility, a large number of people from all over the world come to learn and serve for relatively short periods of time. As a result of this inherent worker turnover, it is immensely challenging to adequately train each worker to properly use specific pieces of equipment. This reality increases the likelihood of equipment misuse and user error.
2. High volume of patients – KH serves a vast number of people across Kenya and neighboring countries. Equipment users are often preoccupied and rushed while providing medical services. The high pace and demand cause an increase in user misuse or mistreatment of the equipment.

3. No user manual – The equipment user may be knowledgeable on the equipment type and purpose, however every brand and version of equipment has operational differences. Access to user manuals help navigate the operational differences to combat potential equipment misuse, however much of the donated equipment does not come with its user manual.

An analysis of the similarities within the above factors led to the realization that the root of the user error issue is imbedded in the internal hospital system. Essentially, the hospital would benefit from a formal training system and protocol library. There is no substitution for time to learn proper equipment usage, but rather the application of policies and guidelines. No device or system can be developed to replace the necessity of time for adequate user training and the need for a complete collection of protocols and procedures. Therefore, user error was eliminated as a focus for the continuation of this study.

Documentation focused study met all the critical parameters targeted in the research decision matrix. Documentation, relative to medical equipment service requests and repairs, also has related impact to a number of other issues evaluated in the decision matrix. Therefore, it was determined as feasible to begin the study focusing on medical equipment service documentation and expand from there.

Deeper investigations revealed how the lack of consistent documentation of equipment services presented several challenges for proper equipment maintenance. The major challenges include:

1. Effective communication – Challenges in effective communication include; the method in which equipment users contact equipment technicians is problematic, the volume of repairs needed is massive, and the technological infrastructure is limited.
2. Time Management – There is an insufficient number of equipment technicians to meet the volume of repair demand leaving little time for proper documentation.
3. Accountability – Technicians are not held accountable for completing and filing maintenance reports.

Because of the potential ability to positively impact these challenges, a device or system to create proper documentation in the area of medical equipment service records was deemed most feasible.

CONCLUSION

Through initial research during the onsite investigation, a list of problem areas was generated. By the systematic matrix and further investigation, it was determined to address issues in documentation. Documentation, with a score of 16 out of a possible 17, posed the highest score showing the highest potential for a notable impact at the hospital. Therefore, an improved documentation system was chosen as the focus for the continuation of this study. Published research, such as that of L. Perry and R. Malkin, has shown the lack of proper documentation in various medical facilities in developing countries [8], so this study's focus and solution will have application beyond KH. The resulting ability to have consistent, reliable documentation, especially with medical equipment services, will provide a firm foundation that will help to improve health and operation outcomes at these medical facilities. We seek to achieve a durable and dependable means for documenting in order to develop a system that can be managed in the developing world.

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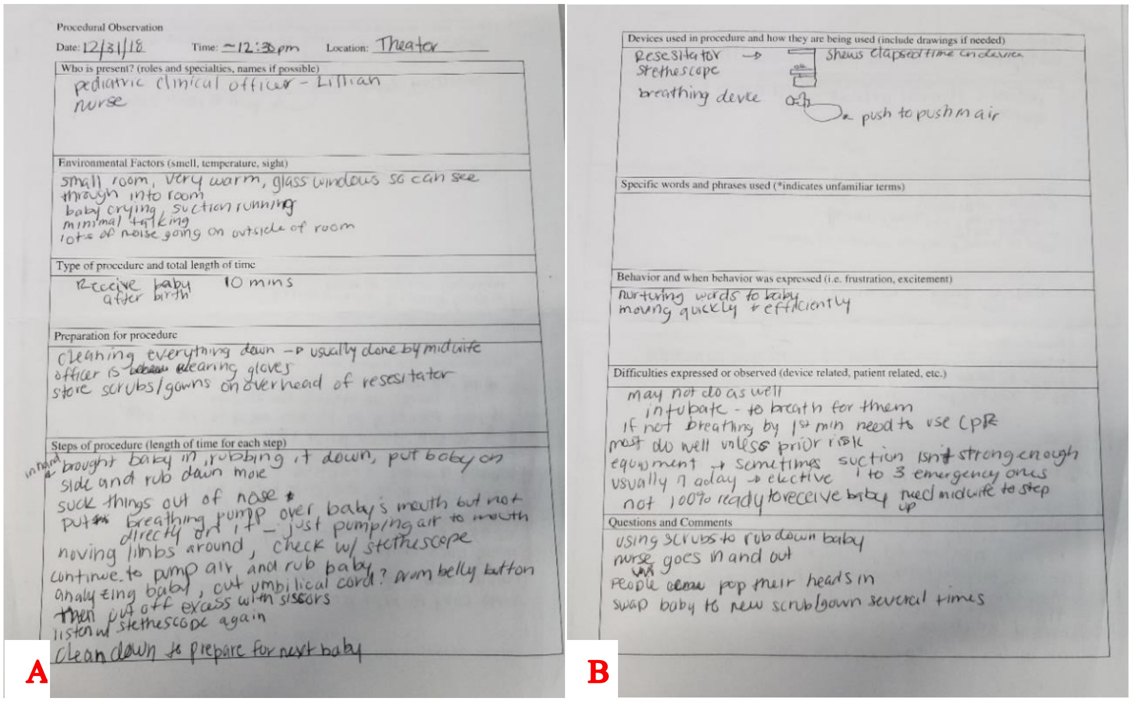
APPENDIX

Appendix A: Procedure observation notes and images



Procedural Observation

Date: 12/31/18 Time: ~12:30pm Location: Theater

Who is present? (roles and specialties, names if possible)

pediatric clinical officer - Lillian
nurse

Environmental Factors (smell, temperature, sight)

small room, very warm, glass windows so can see through into room
baby crying, suction running
minimal talking
lots of noise going on outside of room

Type of procedure and total length of time

Receive baby after birth 10 mins

Preparation for procedure

cleaning everything down → usually done by midwife
officer is wearing gloves
store scrubs/gowns on overhead of resesitator

Steps of procedure (length of time for each step)

in hand brought baby in, rubbing it down, put baby on side and rub down more
suck things out of nose
put breathing pump over baby's mouth but not directly on it - just pumping air to mouth
moving limbs around, check w/ stethescope
continue to pump air and rub baby
analyzing baby, cut umbilical cord? from belly button
then cut off excess with sissors
listen w/ stethescope again
clean down to prepare for next baby

Devices used in procedure and how they are being used (include drawings if needed)

Resesitator → shows elapsed time on device
Stethescope
breathing device push to push in air

Specific words and phrases used (*indicates unfamiliar terms)

Behavior and when behavior was expressed (i.e. frustration, excitement)

nurturing words to baby
moving quickly + efficiently

Difficulties expressed or observed (device related, patient related, etc.)

may not do as well
intubate - to breath for them
if not breathing by 1st min need to use CPR
most do well unless prior risk
equipment → sometimes suction isn't strong enough
usually 7 a day → elective 1 to 3 emergency ones
not 100% ready to receive baby need midwife to step up

Questions and Comments

using scrubs to rub down baby
nurse goes in and out
people pop their heads in
swap baby to new scrub/gown several times

Figure 3: Baby Resuscitation; A) Front of observation notes B) Back of observation notes

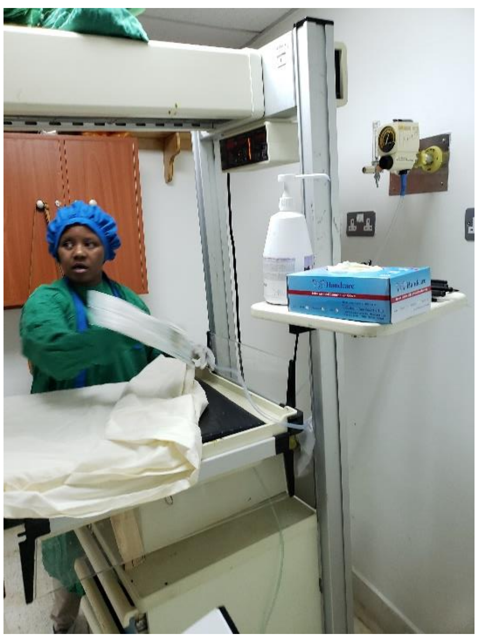
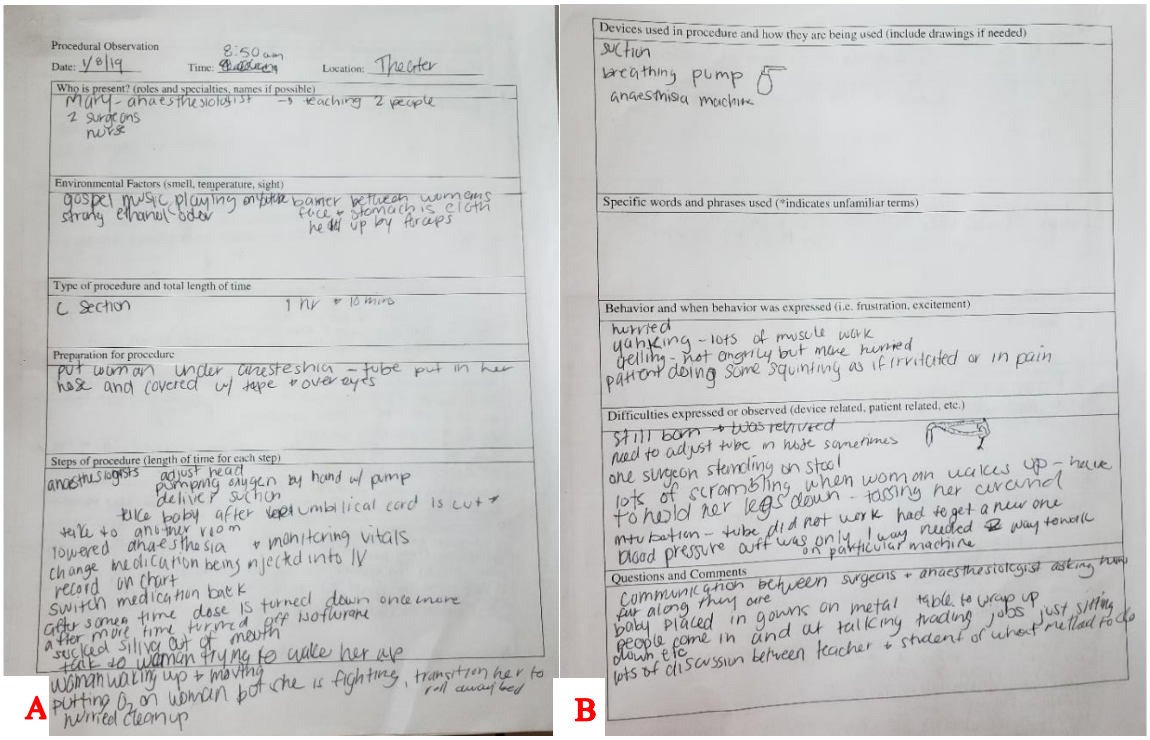


Figure 4: Set up of procedure room for baby resuscitation


A

Procedural Observation

Date: 1/8/19 Time: 8:50 am Location: Theater

Who is present? (roles and specialties, names if possible)
Mary - anaesthesiologist → teaching 2 people
2 surgeons
nurse

Environmental Factors (smell, temperature, sight)
gospel music playing on barrier between womans face + stomach is cloth held up by forceps
strong ethanol odor

Type of procedure and total length of time
C section 1 hr + 10 mins

Preparation for procedure
put woman under anesteshia - tube put in her nose and covered w/ tape + over eyes

Steps of procedure (length of time for each step)
anaesthesiologists adjust head
pumping oxygen by hand w/ pump
deliver suction
take baby after umbilical cord is cut +
take to another room
lowered anaesthesia + monitoring vitals
change medication being injected into IV
record on chart
switch medication back
after some time dose is turned down once more
after more time turned off isoflurane
sucked saliva out of mouth
talk to woman trying to wake her up
woman waking up + moving but she is fighting, transition her to roll away bed
putting O_2 on woman
hurried cleanup

B

Devices used in procedure and how they are being used (include drawings if needed)
suction
breathing pump
anaesthesia machine

Specific words and phrases used (*indicates unfamiliar terms)

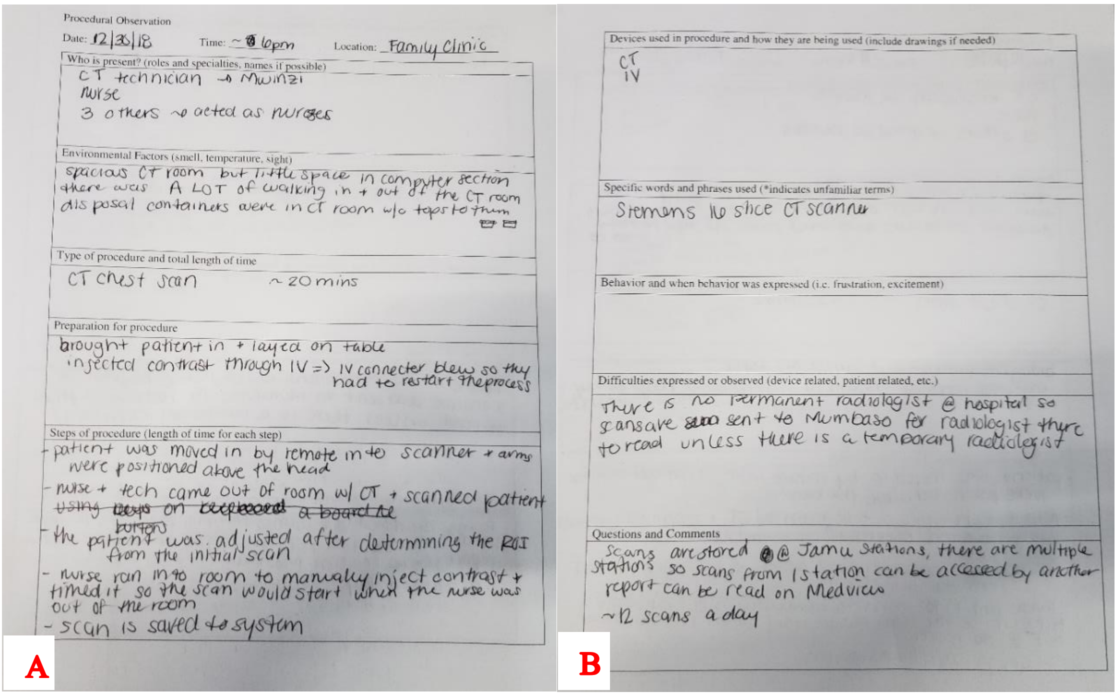
Behavior and when behavior was expressed (i.e. frustration, excitement)
hurried
yanking - lots of muscle work
yelling - not angrily but more hurried
patient doing some squinting as if irritated or in pain

Difficulties expressed or observed (device related, patient related, etc.)
~~still born~~ → was revived
need to adjust tube in nose sometimes
one surgeon standing on stool
lots of scrambling when woman wakes up - have to hold her legs down - tossing her around
intubation - tube did not work had to get a new one
blood pressure cuff was only 1 way needed 2 way to work on particular machine

Questions and Comments
communication between surgeons + anaesthesiologist asking how far along they are
baby placed in gowns on metal table to wrap up
people come in and out talking trading jobs just sitting down etc
lots of discussion between teacher + student of what method to do

Figure 5: Cesarean Section; A) Front of observation notes B) Back of observation notes

Figure 6: Cesarean Section procedure



Procedural Observation

Date: 12/30/18 Time: ~ 6pm Location: Family Clinic

Who is present? (roles and specialties, names if possible)

CT technician → Mwinzi
nurse
3 others → acted as nurses

Environmental Factors (smell, temperature, sight)

spacious CT room but little space in computer section
there was A LOT of walking in + out of the CT room
disposal containers were in CT room w/o tops to them

Type of procedure and total length of time

CT chest scan ~20 mins

Preparation for procedure

brought patient in + layed on table
injected contrast through IV => IV connecter blew so they had to restart the process

Steps of procedure (length of time for each step)

- patient was moved in by remote into scanner + arms were positioned above the head
- nurse + tech came out of room w/ CT + scanned patient ~~using keys on keyboard a board the~~ button
- the patient was adjusted after determining the ROI from the initial scan
- nurse ran into room to manually inject contrast + timed it so the scan would start when the nurse was out of the room
- scan is saved to system

A

Devices used in procedure and how they are being used (include drawings if needed)

CT
IV

Specific words and phrases used (*indicates unfamiliar terms)

Siemens 16 slice CT scanner

Behavior and when behavior was expressed (i.e. frustration, excitement)

Difficulties expressed or observed (device related, patient related, etc.)

There is no permanent radiologist @ hospital so scans are sent to Mombasa for radiologist there to read unless there is a temporary radiologist

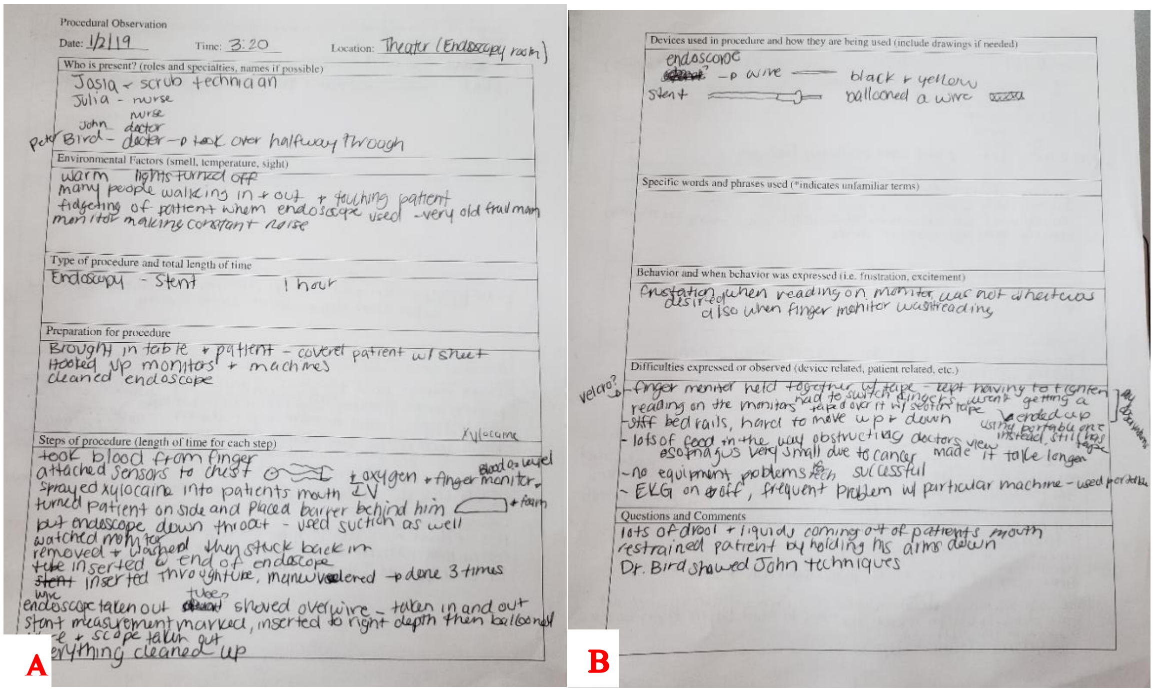
Questions and Comments

Scans are stored @ Jamu stations, there are multiple stations so scans from 1 station can be accessed by another
report can be read on Medview
~12 scans a day

B

Figure 7: CT Scan; A) Front of observation notes B) Back of observation notes

Figure 8: CT Scan procedure



Procedural Observation

Date: 1/2/19 Time: 3:20 Location: Theater (Endoscopy room)

Who is present? (roles and specialties, names if possible)

Josia - scrub technician
Julia - nurse
John nurse doctor
Peter Bird - doctor → took over halfway through

Environmental Factors (smell, temperature, sight)

warm lights turned off
many people walking in + out + touching patient
fidgeting of patient when endoscope used - very old frail man
monitor making constant noise

Type of procedure and total length of time

Endoscopy - Stent 1 hour

Preparation for procedure

Brought in table + patient - covered patient w/ sheet
Hooked up monitors + machines
cleaned endoscope

Steps of procedure (length of time for each step)

Xylocaine
took blood from finger
attached sensors to chest + oxygen + finger monitor, Blood O_2 level
sprayed xylocaine into patients mouth IV
turned patient on side and placed barrier behind him + foam
put endoscope down throat - used suction as well
watched monitor
removed + washed then stuck back in
tube inserted @ end of endoscope
~~stent~~ inserted through tube, maneuvered → done 3 times
endoscope taken out wire tubes shoved over wire - taken in and out
stent measurement marked, inserted to right depth then ballooned
wire + scope taken out
everything cleaned up

Devices used in procedure and how they are being used (include drawings if needed)

endoscope
→ wire black + yellow
stent ballooned a wire

Specific words and phrases used (*indicates unfamiliar terms)

Behavior and when behavior was expressed (i.e. frustration, excitement)

frustration when reading on monitor was not what was desired
also when finger monitor wasn't reading

Difficulties expressed or observed (device related, patient related, etc.)

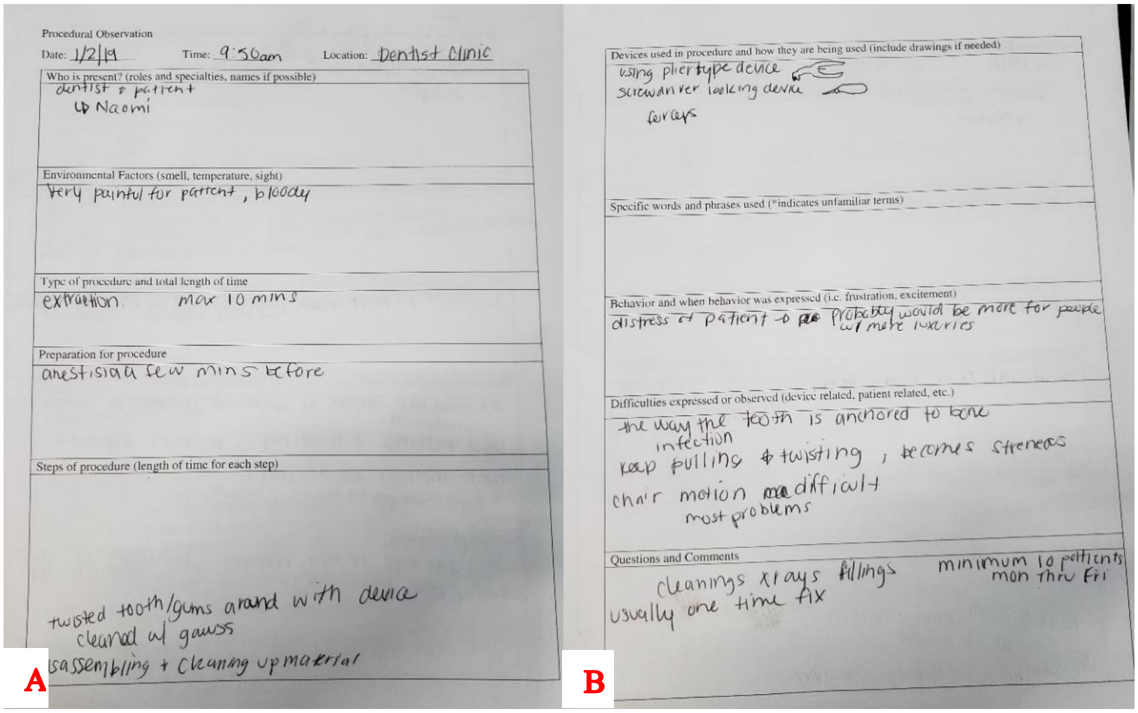
velcro? → - finger monitor held together w/ tape - kept having to tighten had to switch fingers weren't getting a reading on the monitors taped over it w/ scotch tape
- stiff bed rails, hard to move up + down ended up using portable one instead, still has tape
- lots of food in the way obstructing doctors view
esophagus very small due to cancer made it take longer
- no equipment problems tech successful
- EKG on + off, frequent problem w/ particular machine - used portable

Questions and Comments

lots of drool + liquids coming out of patients mouth
restrained patient by holding his arms down
Dr. Bird showed John techniques

Figure 9: Endoscopy Procedure; A) Front of observation notes B) Back of observation notes

Figure 10: Set up of Endoscopy room for procedure



Procedural Observation

Date: 1/2/19 Time: 9:50am Location: Dentist Clinic

Who is present? (roles and specialties, names if possible)

dentist + patient

Naomi

Environmental Factors (smell, temperature, sight)

very painful for patient, bloody

Type of procedure and total length of time

extraction max 10 mins

Preparation for procedure

anestisia few mins before

Steps of procedure (length of time for each step)

twisted tooth/gums around with device

cleaned w/ gauss

disassembling + cleaning up material

A

Devices used in procedure and how they are being used (include drawings if needed)

using plier type device

screwdriver looking device

forceps

Specific words and phrases used (*indicates unfamiliar terms)

Behavior and when behavior was expressed (i.e. frustration, excitement)

distress of patient → probably would be more for people w/ more luxuries

Difficulties expressed or observed (device related, patient related, etc.)

the way the tooth is anchored to bone

infection

keep pulling & twisting, becomes strenous

chair motion difficult

most problems

Questions and Comments

cleanings xrays fillings minimum 10 patients mon thru Fri

usually one time fix

B

Figure 11: Tooth Extraction; A) Front of observation notes B) Back of observation notes

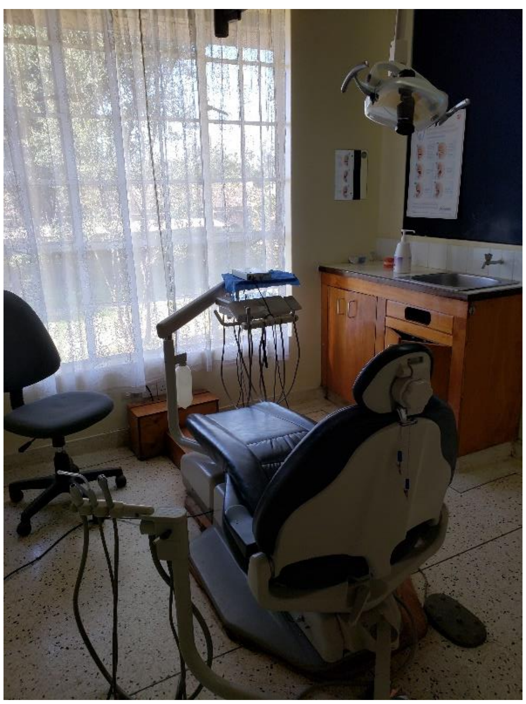


Figure 12: Procedure room for tooth extraction

Appendix B: Images and Description of KH Medical Equipment

Figure 13: Autoclave in Theatre Department

- Very crucial, necessary to sterilize material
- Needs a water filter to ensure water source is clean
    - Water softener was unsuccessful
    - Current filtration burns elements
    - Desired filtration is expensive
- Generator requires repairs at times

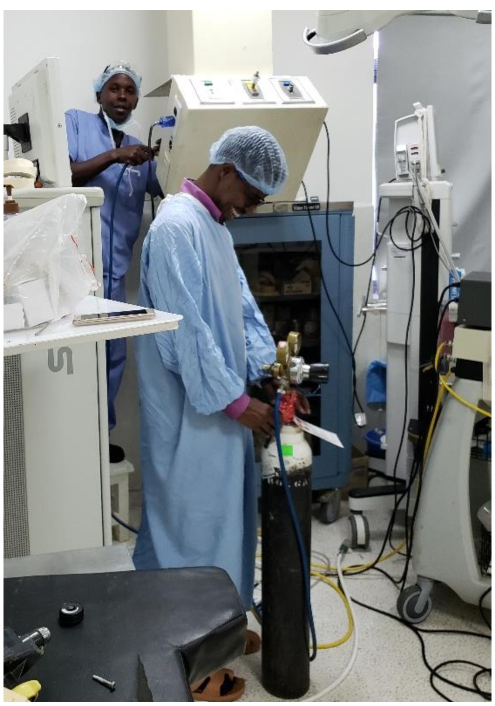


Figure 14: Suction blockage repair in Theatre Department

- Issues have become more prevalent since 2018
- Waste bottles fill up and begin to come back through the suction system clogging the filter
- Blockage repaired by washing the filter with water
- Filter change needs are not tracked

Figure 15: Patient monitor in Casualty Department

- Brought in from companies in Kenya
- Recently replaced in 2018
- Experience electrical problems yet tend to be an easy fix

Figure 16: Heaters in inpatient wards

- Located in each room
- Crucial for keeping the patients warm
- Experience shortages

Figure 17: Patient beds in Men's Ward

- Issues with controlling the movement
- Only a few are electrical, others are manual

Figure 18: Ventilator used in Theatre Department and Intensive Care Unit (ICU)

- Three versions: Carescope, Carestream, and Nellcor Puritan Bennett
  - Nellcor Puritan Bennett is the oldest but works the best
- When individual parts breakdown, able to repair that specific part without taking apart entire machine
- Issues
  - Filter gets oily from oxygen source
  - Oxygen sensors need to be replaced
  - Batteries wear out and need to be replaced

Figure 19: Incubator in Pediatric ICU

- All incubators are donated, currently 8 in use
- Most issues require a spare part which are difficult to access
    - Procurement process goes from Kijabe to Nairobi to manufacturing country, takes at least 3 months

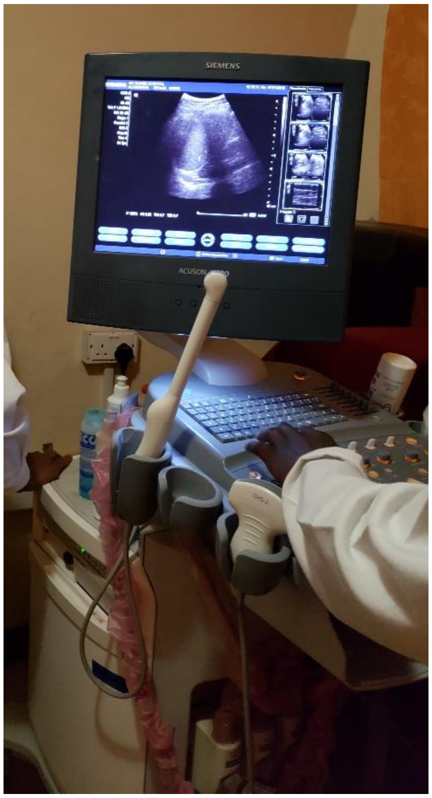


Figure 20: Siemens Acuson x300 Ultrasound Machine

- Not serviced regularly
- Images can’t be sent to PAC because of the difference in the format
- Don’t have license to necessary software required and it is very costly
- Images are saved on disk or on the system and when it gets full they are deleted
- Does not get good contrast
- Images are read immediately by sonographers
    - A report is written then typed up using template on hospital system and saved to the system
- 50 people seen a day for an ultrasound scan
- 2+ years old

Appendix C: Discovered Needs/Issues Decision Matrix

Table 5: Decision matrix for 29 needs observed and expressed at Kijabe Hospital

Criteria	*Scale*	Equipment User Error	No Permanent Radiologist	Unprepared for procedures
Frequency of Issue	1=once 2= more than once	2	2	1
Feasibility	1-5 (5=highly likely)	5	1	3
Interest	1-5 (5=strongly aligns)	4	3	2
Affordability	1-5 (5=low cost)	4	1	3
Total	**Out of 17**	**15**	**7**	**9**
Criteria	Documentation	Patient Monitor Malfunction	International Purchasing	Suction Blockage
Frequency of Issue	2	2	2	2
Feasibility	5	2	3	5
Interest	4	1	3	3
Affordability	5	2	2	3
Total	**16**	**7**	**10**	**13**
Criteria	Food Obstruction during Endoscopy	Ultrasound Quality	Stiff Bed Rails	Electric Chair Malfunction
Frequency of Issue	1	1	1	2
Feasibility	5	1	4	3
Interest	1	3	1	1
Affordability	5	1	3	2
Total	**12**	**6**	**9**	**8**
Criteria	X-ray Height Limitation	Spare Parts	Heaters malfunction	Ventilators Malfunction
Frequency of Issue	1	2	2	2
Feasibility	2	4	3	1
Interest	3	4	1	1
Affordability	1	3	2	2
Total	**7**	**13**	**8**	**6**
Criteria	Store Ultrasound Images to PACS	Convenient EEG	X-ray Cassettes	Endoscopy Printer Quality
Frequency of Issue	2	1	1	1

Feasibility	4	1	2	2
Interest	4	2	2	2
Affordability	4	1	1	2
Total	**14**	**5**	**6**	**7**
Criteria	Anesthesia Machine Malfunction	Manual Staining in Pathology	Strenuous Tooth Extraction	Electrical System Upgrade
Frequency of Issue	2	1	1	1
Feasibility	1	2	3	3
Interest	1	1	1	1
Affordability	2	1	3	1
Total	**6**	**5**	**8**	**6**
Criteria	Technician Training	Microtome Malfunction	Faulty X-ray Motion	Autoclave Water Filter
Frequency of Issue	2	1	1	2
Feasibility	5	1	3	4
Interest	3	1	2	3
Affordability	3	2	3	3
Total	**13**	**5**	**9**	**12**
Criteria	EKG Malfunction	Low supplies		
Frequency of Issue	1	2		
Feasibility	2	2		
Interest	1	2		
Affordability	2	1		
Total	**6**	**7**		

Chapter III: Mobile Documentation System for Medical Equipment Servicing in Developing Countries

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ABSTRACT

Developing countries have variable healthcare resources including limited expertise, reliable medical equipment, and unstable infrastructure. They rely heavily on donated medical equipment from high income countries just to provide necessary and common medical attention. Such charitably donated equipment challenges their technological infrastructure, available monetary resources, and human resources due to ongoing repair needs. A team from Wake Forest Baptist Medical Center – Rayonna Gordon and Evelyn Anthony – confirmed this situation during a two-week intensive investigation at AIC Kijabe Hospital in Kijabe, Kenya. AIC Kijabe Hospital experiences a significant number of equipment failures daily; averaging over 10,000 reported issues each year, often leaving equipment sitting unused. Out of service equipment has an adverse effect on patient access to care within the country and in neighboring countries. Currently there is a gap in the communication network of maintenance and management systems at resource-limited facilities hindering the monitoring and timely repair of medical equipment to help sustain good medical care. The objective of this study is to design and develop a readily deployed method of recording and tracking equipment services in resource-poor medical facilities.

The Medical Equipment Network Documentation System (MENDS) was created to provide an automated system that captures and documents information about requests and repairs of medical equipment. When equipment fails, the user can submit a work order request for service through MENDS that alerts the Biomedical Engineering team. MENDS will assign the work order request to one engineer and once the job is complete

the engineer will submit a report to MENDS that closes the loop. MENDS collects the necessary information in real time and saves it to an online database.

A preliminary test completed at Wake Forest Baptist Medical Center confirmed the functionality and usability of MENDS. The results from the test concluded 75% of users were satisfied overall with MENDS. The test feedback facilitated optimization of MENDS ahead of implementation in its intended in country site. MENDS should decrease equipment downtime by improving responsiveness and record keeping. The collection of information will create a resource to increase repair efficiency and procure upgraded equipment when current equipment is end-of-life as shown by repair records. MENDS can be scaled for other global healthcare settings and be a source of information for improved accessible medical equipment.

Keywords:

Developing countries

Resource-poor medical facilities

Donated medical equipment

Automated documentation

Medical facility communication network

Equipment repair efficiency

Accessible medical equipment

INTRODUCTION

During an investigation at AIC Kijabe Hospital (KH), in Kijabe, Kenya, it was revealed that the donated equipment challenges the technological capacities of the hospital, including available wireless internet, and the skill set of the biomedical engineers responsible for maintenance. These donations are the facility's main resource for procuring equipment for which they rely heavily. KH experiences a significant number of failures and breakdowns daily on the equipment, estimating an average of over 10,000 reported issues each year. Inoperative equipment limits the care provided at the facility, which can adversely affect access to care for a substantial number of Kenya's population as well as neighboring countries. The hospital's solvency is from patient revenues and fundraising, which does not generate sufficient profit to obtain additional resources, expensive updates, and repairs to equipment [1].

It is crucial to have a strong maintenance and management system to address the need of donated equipment in resource-limited settings [2]. A robust system would improve turnaround time of out of commission equipment so needed equipment remains in service. The current maintenance systems rely on manual record keeping and follow-up. Service requests are either written on paper or equipment users contact the engineers via phone calls. Afterward service reports are written in a notebook or typed and saved on the engineering department's computer. Though this method is inexpensive and easy to use, it leaves much room for error and inconsistency. There is very limited access to the documents and, for paper records, storage and safekeeping become a concern [3]. Occasionally resource-limited facilities will use online programs to sustain their maintenance system. An online portal, open to key personnel, prompts the user to input specific information about the service needed. Engineers enter into that same portal to view the details of the request in order to complete the service. Afterward they themselves are prompted to input specific details about the service completed. Though this process is comprehensive, it is also time consuming and inconvenient.

There is a need for comprehensive medical equipment maintenance and management system to strengthen the communication network and monitor repair needs and timelines so needed equipment remains in service. This study focuses on the development and preliminary off site testing of a user friendly communication network for reporting and tracking the equipment repair processes, thereby improving documentation quality and quantity. The aim of this study is to verify the developed system operates as desired and optimize it for its intended setting.

METHODS

The goal was to create an automated system that captures and documents information about service requests and repairs of medical equipment – a system named the Medical Equipment Network Documentation System or MENDS. MENDS is a mobile device based system that facilitates and records service requests from equipment users and status reports from equipment engineers, creating an ongoing digital log of equipment service information.

MENDS uses short message service application programming interface (SMS API) software to allow for the use of text messaging as the form of communication between MENDS and the equipment user or engineer [4]. The rationale for choosing text messaging as the form of communication is to avoid the need for internet access yet maintain a quick and simple approach. A mobile application may be more user friendly;

however, they rely heavily on internet access or an individual's mobile data capacity. Majority of Kenyan residents have mobile phones, but only 26% use the internet [5]. Also, mobile applications are not easily transferrable across manufacturers. Though SMS is not a highly user friendly interface, it is the most efficient and cost effective method given the unreliable nature of wireless internet at these facilities. Using a dedicated shortcode increases the cost efficiency of text messaging because it acts as a toll free number which is no cost to the users; so the only requirement would be for the user to have a cellular device and service. Plivo Inc. (San Francisco, California) was the SMS API platform chosen for this study to accomplish the text messaging capabilities. Plivo Inc. was used at a rate of $0.005 per outgoing text message which met the cost effective criteria. Information documented through MENDS is backed up using DigitalOcean Inc. (New York, New York), an online cloud server which cost $5 per month to host. The server can be accessed through the web address www.mends.xyz. With the proper password, any authorized personnel can open the log of captured equipment servicing data.

Input was received from the KH Biomedical Engineering Department (Biomed) to determine the specific data that a new system should capture as well as the ideal user criteria. Multiple meetings and surveys were held with KH Biomed to determine that the minimum information needed in a service request. The information is as follows:

- Department Name
- Type of Machine/Device
- Contact Name
- Issue/Failure Type

- Urgency of Request
- Date

It was also determined that the minimum information needed in a service report is as follows:

- Date Completed
- Service Performed
- Repairman Name

The engineers expressed that ideally a system would be most beneficial if:

- Encompasses all necessary information
- Easily identifies common equipment issues and their solutions
- Is able to access equipment history
- Can be used as proof of work
- Traces services for ease of follow up
- Is quick and easy to use
- Provides alerts for any pending work
- Offers data showing current status of equipment
- Is convenient
- Is reliable in emergency situations

Design

Operation Process. MENDS operates in a specific flow of information that is outlined in the text below. A flowchart of the process can be seen in Appendix D.

When there is an issue with equipment in the medical facility, the equipment user will submit a work order request for service by contacting MENDS. The text message will detail the equipment type, the department location, the specific issue the equipment is having, the urgency, and the user’s name. MENDS will ask the user to verify the information that it has received, and once verified, will send an alert to all the biomedical engineers at the facility. The alert contains the details of the work order request and asks each engineer to either accept or decline. Each engineer will send their acceptance or rejection via text message, and MENDS will choose one of the engineers for assignment. The work order assignment is based on engineer availability and number of outstanding work orders.

Once the work order has been assigned to an engineer, the engineer is responsible for tending to the request. That engineer will submit a status report upon completion of the assignment. They will do this by contacting MENDS using text messaging detailing a description of what was done to the equipment, how much it cost, if additional work is needed, and if the use of the equipment has stipulations. MENDS will ask the engineer to verify the information entered; once verified MENDS will close out the work order and send a status notification to the requesting user. The notification will indicate one of the following:

1. “The work order is complete.”
2. If the engineer answered yes to the question ‘is additional work still needed on the equipment,’ the notification will read; “The work order is complete. Additional work is needed on the machine.”

3. If the engineer answered yes to the question ‘are there any stipulations on the use of the equipment,’ the notification will read; “The work order is complete. There are stipulations on the use of the machine. Contact engineer for more information”
4. If the engineer answered yes to both questions ‘is additional work still needed on the equipment’ and ‘are there any stipulations to the use of the equipment,’ the notification will read; “The work order is complete. Additional work is needed on the machine. There are stipulations on the use of the machine. Contact engineer for more information”

MENDS saves the information onto the cloud server during this process, which can be viewed in real time.

Accuracy control. MENDS has several features, which allow it to assist the user and engineer in capturing accurate information. If the information is texted to MENDS in the incorrect format, MENDS will automatically send a reply containing a template for appropriate submission. The format enables MENDS to properly log in the information in the online server. If the information was submitted in the correct format but contains incorrect details, the user or engineer has an opportunity to correct it in the verification step, i.e. MENDS will ask the user or engineer to read and verify entered information or resubmit the details with the corrected information. MENDS will ask for verification again showing the corrected details.

Time Control. Several features of MENDS help ensure work is performed in a timely manner. A reminder text is sent to all the engineers once a week with the work order numbers of any open service requests. A work order is considered open for the following reasons:

1. The request has been accepted and assigned, but a status report has yet to be submitted.
2. An engineer answers yes to the question "is additional work still needed on the equipment."

To close out open work orders, an engineer will need to submit a report for that work order stating that repairs are fully complete.

The assignment step of the process is regulated by time limits. As stated earlier, the work order is assigned based on engineer availability and number of outstanding work orders. There is a five-minute window between acceptance by the first engineer and assignment of the work order. This allows all the available engineers to accept the request. After that five-minute window, MENDS assigns the work order to the engineer with the fewest open work orders. This is to ensure that work is divided equitably among engineers at the facility. For all the engineers that decline the request, they are given a 15-minute grace period where no new request alerts will be sent to them. This feature allows time for the engineer to complete current work without interruption. If no engineer responds to the request or if all the engineers decline the request, MENDS will resend the same alert every 30 minutes until at least one engineer accepts the request. This feature ensures that no request is forgotten and prevents the users from having to locate the engineers themselves to address unanswered requests. The above mentioned time limits were formed as a result of discussion and input from KH Biomed based on their work environment and practice patterns.

Testing Method

The preliminary test was performed in Winston Salem, NC using Wake Forest Baptist Medical Center (WFBMC) personnel. This location was chosen because it was local, convenient, and closely resembles the intended setting, that is; it is a medical facility and employs the type of personnel for which MENDS was designed. Four technicians from the Clinical Equipment Management Department volunteered to serve as the engineers and over 25 WFBMC employees volunteered to be the equipment users for the test. Two days prior to the test, the four engineers were briefed on how to use MENDS and what to expect.

The day before and the day of the test the equipment users were given a flyer handout, which can be seen in Appendix E, and an explanation on how to use MENDS. The test began at 9:00am and ended at 5:00pm on Friday September 6, 2019 representing a full work day. Users were instructed to send fictional requests to MENDS according to the instructions given. No limits were placed on the number of service requests they could submit during the testing period. Figure 21 shows sample fictional requests given to several users who had difficulty formulating their own examples.

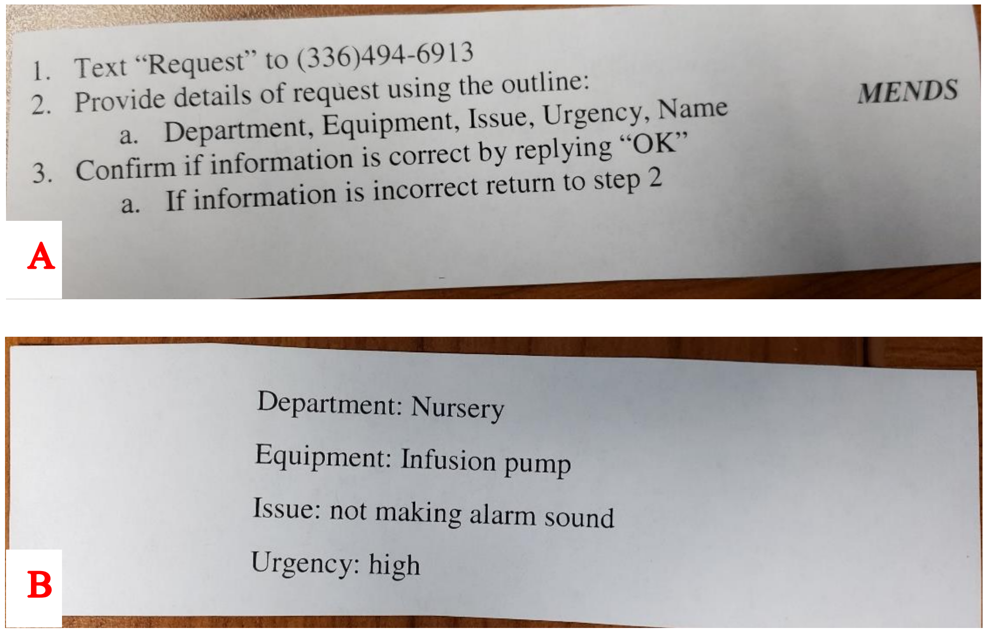

Figure 21: A) Front: 3 step directions for users on requesting service B) Back: sample request information to use

As requests came through MENDS, the engineers responded to the alerts and submitted fictional status reports for the work orders assigned by MENDS.

During the testing period, MENDS was monitored as well as the information being captured on the cloud server. Modifications were made as necessary to achieve desired function and are detailed in the Discussion section of this study. Once the testing period was complete, a survey was sent to eight of the users whom which hold medical positions most closely related to those at the intended setting. The survey was to evaluate the function of MENDS and their opinion on its utility. Results and feedback of the survey are discussed in the Results section of this study.

RESULTS

The surveyed users were asked to rate their agreement with each statement on a 5 point Likert scale with 1 being strongly disagree/very unsatisfied and 5 being strongly agree/very satisfied. They responded to the following statements:

- Overall satisfaction with MENDS
- MENDS is simple to use
- I am able to quickly request equipment service
- I am able to effectively submit a request for equipment service
- It was easy to learn how to use MENDS
- The text message interface with MENDS is pleasant
- The terminology in the messages is clear and easy to understand
- The supplementary information (quick guide flyer) provided for MENDS is clear and easy to understand
- It was easy to remember how to use MENDS without the supplementary information
- It was easy to correct mistakes using MENDS
- I feel comfortable using MENDS

Figure 22 records the user survey ratings. The data shows that at least 62.5% of the users strongly agreed (rating of 5) with each statement of the survey. There were zero responses of strongly disagree or disagree (rating of 1 and 2) for each statement as well. Four out of the eleven statements received one or more rating of 3, indicating a neutral position on the statement. The highest number of neutral ratings was given to the statement “It was easy to correct mistakes using MENDS.”

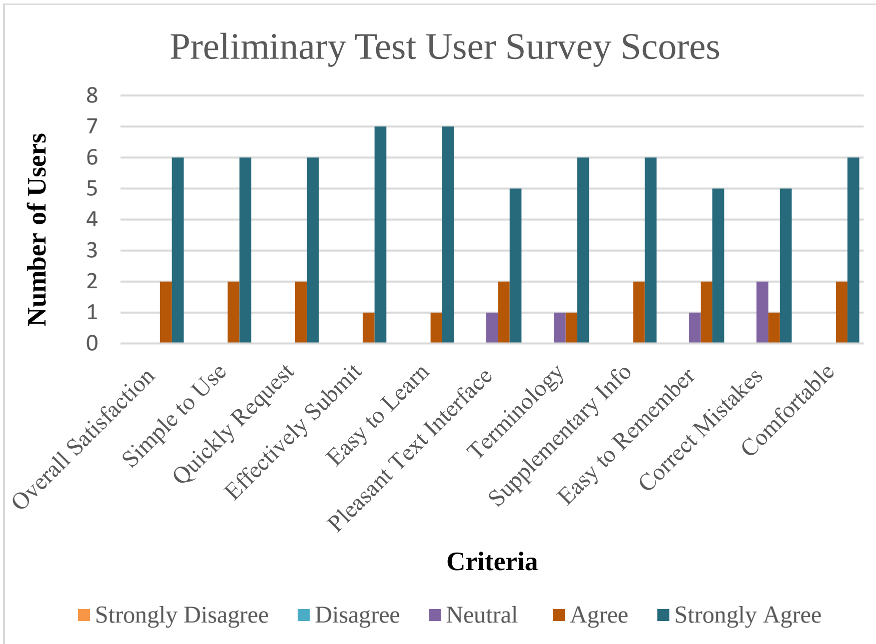

Figure 22: User survey scores from the WFBMC preliminary test rated from 1-5, 1=strongly disagree/very unsatisfied and 5=strongly agree/very satisfied

The survey also provided the users an option for free text comments regarding MENDS. The feedback can be seen in the list below.

- Problem description field formatted better to make more user friendly
- Formatting and syntax can be improved
- Need consistency with spacing and text format
- Updates would be beneficial
- Concern of using personal phone
- What happens when typos are made?
- Who to contact for troubleshooting?
- What happens when cell service is unavailable?

- Quick and simple to use
- Easy interface
- Nice system
- Everything was great
- No need for improvements

A portion of the above comments identified the format and syntax of the text messages sent from MENDS as awkward and not user friendly. Other comments also addressed being able to make corrections to the details or the format submitted to MENDS when making a service request.

DISCUSSION

The outcome from the preliminary test confirms the functionality and usability of MENDS. Modifications and adjustments were made based on data captured from monitoring MENDS during the test, preliminary test results, and relevant feedback. Table 6 describes the issues resolved while monitoring MENDS during the testing period.

Table 6: Issues with MENDS detected during the testing period and their resolution and reasoning

Issue	Resolution	Reasoning
Text messages need to be all capitalized letters for MENDS to register the information.	Altered MENDS to accept text in all capitalization, no capitalization, or a mixture of capitalized and non-capitalized letters.	To ease the process for the user and minimize the need for corrective messages.
When typing in the word "request" users received a verification text instead of the outline for submitting a request.	Reconfigured MENDS so the user would receive the outline message from MENDS to show the format they are to follow to submit the details.	Novice users or those who have forgotten the proper format need instruction on proper submission so MENDS can collect information correctly.
The department specification for each request was not shown in the online database.	Revised the content in the database to ensure that all information submitted via text was shown in the online server.	All details need to be captured and recorded in order to give MENDS the comprehensiveness required.
Users were not informed of when the work order was completed.	Updated the system so the requesting user would receive a status notification once the service report was submitted.	To maintain effective communication between user and engineer, the user must be kept abreast of the status of the equipment.
Engineers were not being reminded of work orders that have not been assigned.	Modified MENDS so that it would resend any unassigned service requests after 30 minutes has passed.	All service needs must be attended to in order to keep equipment in use and these reminders hold the engineers accountable.

Because of helpful feedback on the format and syntax of the messages sent by MENDS, the code was redesigned to make the messages more understandable. The possible changes were limited due to the number of text characters allowed and the cost per message. Clarifying punctuation were incorporated in the messages and changed the spacing to make it more readable. These changes were most important for the verification step, for which appropriate line breaks were incorporated, so that the user could effortlessly read each detail for accuracy.

Also, changes were made to the training and deployment process for MENDS in response to the low score on the survey statement, “It was easy to correct mistakes using MENDS.” For this preliminary test, training only consisted of a quick explanation via email and the quick guide flyer seen in Appendix E. The engineers received an in person five-minute explanation of their responsibilities and proper usage two days prior to testing. It was apparent that these methods did not allow enough time or opportunity for in depth descriptions that would have enhanced clarification. Also, test day was the first personal encounter with MENDS for all of the users and engineers which did not allow much time for the learning curve.

To better introduce MENDS to new users, these training methods were replaced with a video tutorial. The video tutorial describes MENDS and its various functions with examples of each step. The video was posted on YouTube.com to be accessed by user and engineer at any time. This tutorial video will be combined with a full length in person presentation of MENDS giving each user and engineer an opportunity to become comfortable with the new technology before daily use in the field. This change will help users remember how to use MENDS, including how to correct mistakes, and better engage with the text interface. The range of the aesthetic and functional changes will be tested further during the in country deployment phase at KH.

CONCLUSION

Based on the results of the preliminary test of MENDS and the modifications made from the test results, feedback, and observed issues during the test, MENDS can confidently advance to the next stage of testing in Kenya. MENDS has proven to operate as desired and, following the adjustments and improvements made, it has been optimized for use in its intended setting. The next step is to conduct a three-month test of MENDS at KH with several departments in order to get a broad scope of different equipment and levels of demand. The data from an on-site test will be analyzed against current equipment repair reporting and tracking method.

It is believed that this future work will reaffirm the function of MENDS as well as validate its usefulness and efficacy in the field. It is fully anticipated that MENDS will decrease equipment downtime by improving responsiveness and record keeping. MENDS will create a resource for engineers to increase efficiency of repairs as well as a basis of evidence to procure replacement equipment when current devices are end-of-life. Future directions for MENDS involves scaling it for hospital networks or partnerships and applying it in a range of global healthcare settings.

ACKNOWLEDGEMENTS

We would like to acknowledge and thank the organizations whose funding supported this study. These organizations include Wake Forest University Biomedical Engineering Department, Wake Forest University Graduate School, Wake Forest University Radiology Department, Phi Kappa Phi Honor Society, Patreon donors, and Mt. Nebo Baptist Church of Blackstone, VA.

We would also like to acknowledge the Biomedical Engineering team and other staff members at AIC Kijabe Hospital. Finally, thank you to the Wake Forest Baptist Medical Center personnel for their participation in the preliminary test, especially the Clinical Equipment Management Department employees.

DISCLOSURES

There are no disclosures for all authors.

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APPENDIX

Appendix D: Flowchart of MENDS operational process

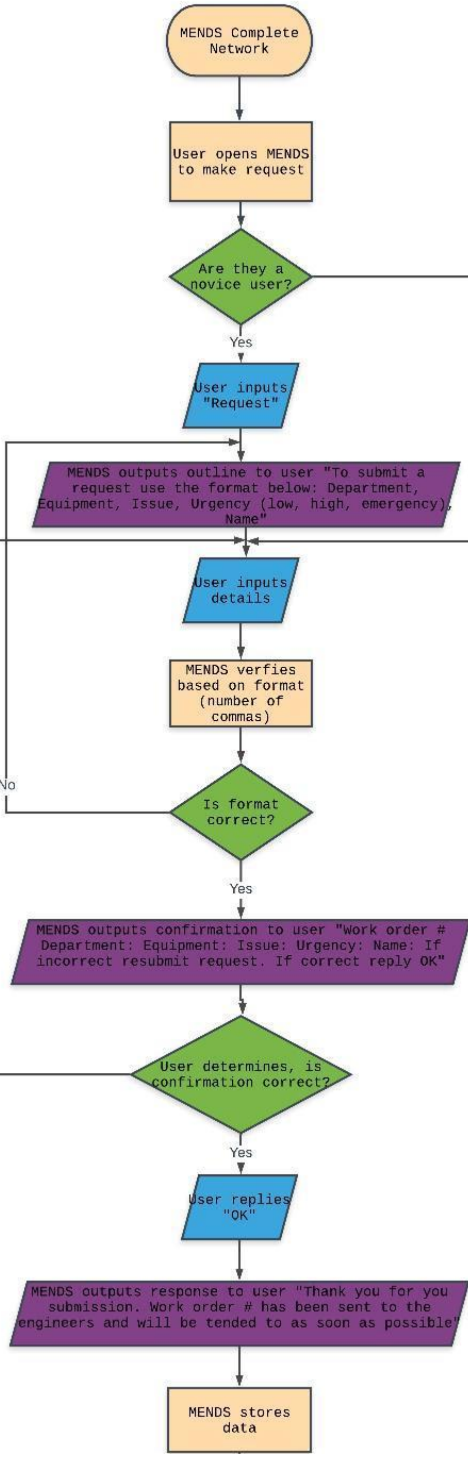

Figure 23: Flow chart for requesting process of MENDS

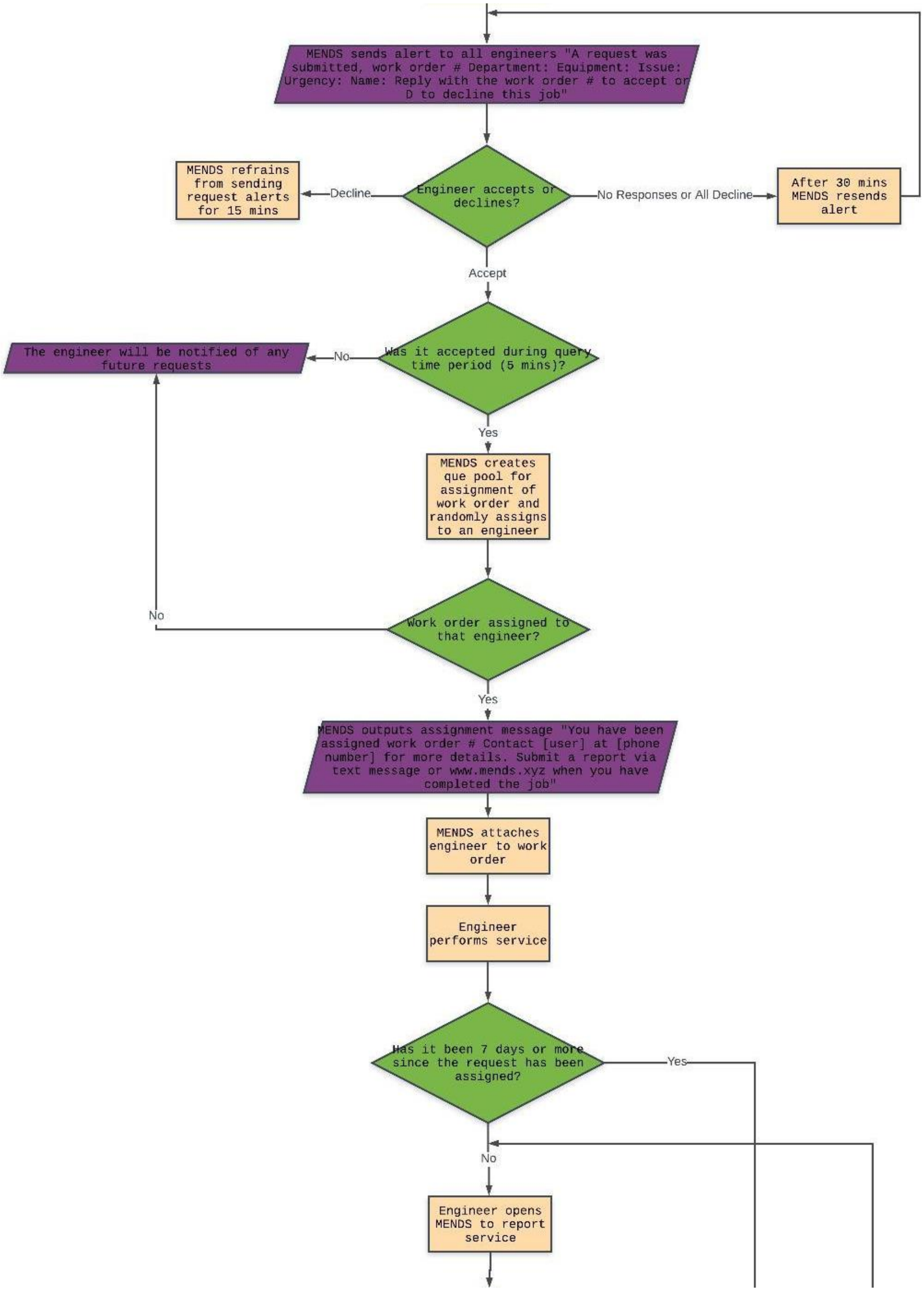

Figure 24: Flow chart for assigning process of MENDS

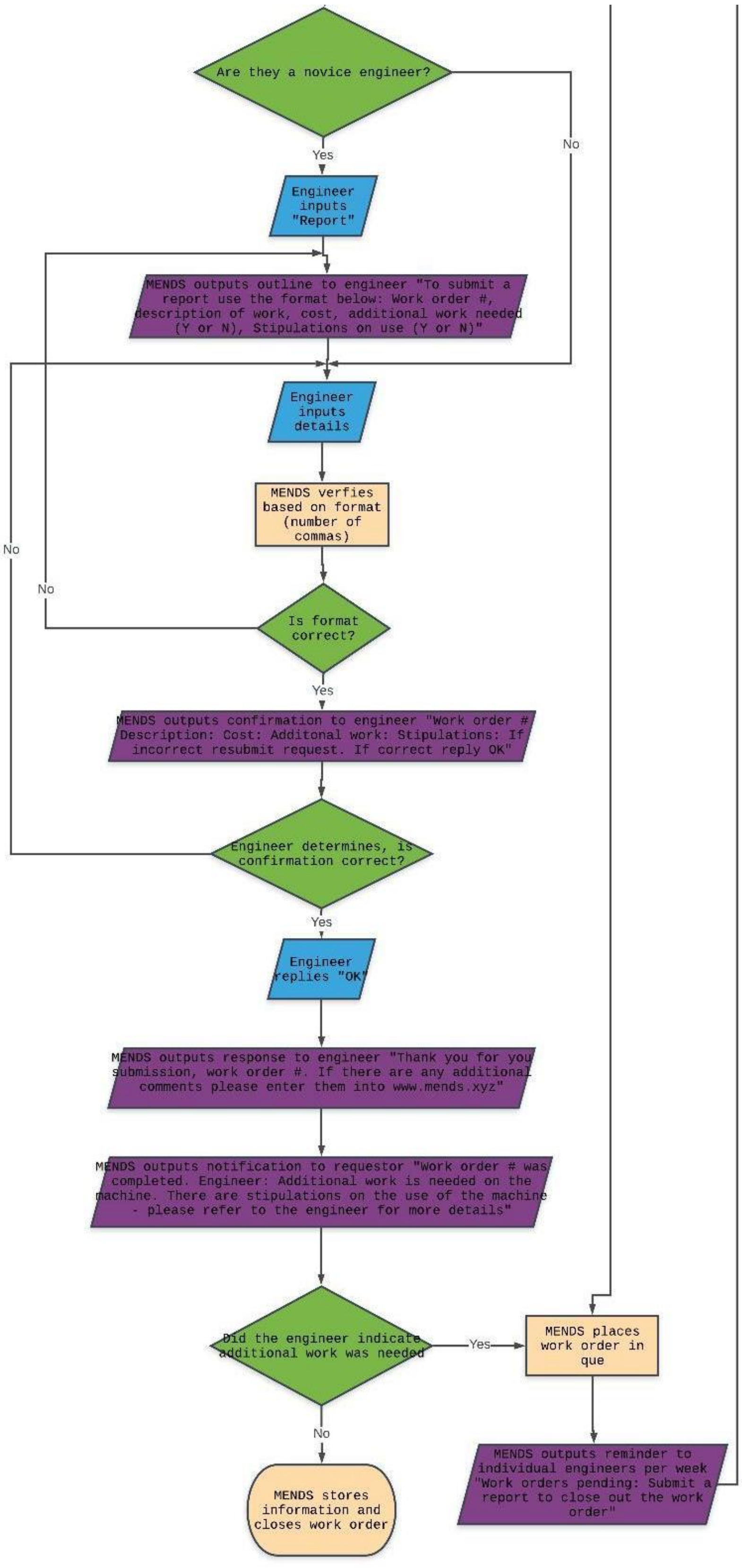

Figure 25: Flow chart for reporting process of MENDS

Appendix E: Quick guide flyer with instructions on using MENDS

MENDS Equipment Services Quick Guide

Our **Medical Equipment Network Documentation System** (MENDS) tracks and documents medical equipment service requests and repairs all from your mobile device.

MENDS uses text messaging to facilitate communication between you and the requestor with *ease and efficiency* as well as stores all your information.

Assigning Medical Equipment Service

MENDS will alert you of a new request

- You will receive a message from (336) 494-6913 with the details of a new requested service and the work order number

Accept or Decline

- Accept the new request by replying with only the work order number of the request
- Decline the new request by replying with "D" for Decline

Tend to service

- If you accepted the request you will receive a message either assigning you the work order or informing you that the work order was assigned to another engineer
- If it was assigned to you, you are responsible for tending to that work order and submitting a report

Reporting Medical Equipment Service

1

Contact MENDS to submit a report

- Text "REPORT" to (336) 494-6913

2

Provide details

- Follow the outline provided to give the necessary information about the repair
  - Outline: Work Order Number, Description of Work Completed, Cost (in KSH)
  - You will be asked if any additional work is necessary and if there any stipulations on the use of the machine. Reply "Y" for Yes or "N" for No

3

Confirm information

- Ensure the information in the confirmation text you receive is correct
  - If it is correct reply "OK"
  - If it is incorrect, resend the details using the same outline

You will get a reminder each week about any open work orders – including those for which you have yet to submit a report for as well as those that you indicated need additional work.

Submit a report to close out all work orders.

Figure 26: Engineer Quick Guide flyer with instructions on how to use MENDS

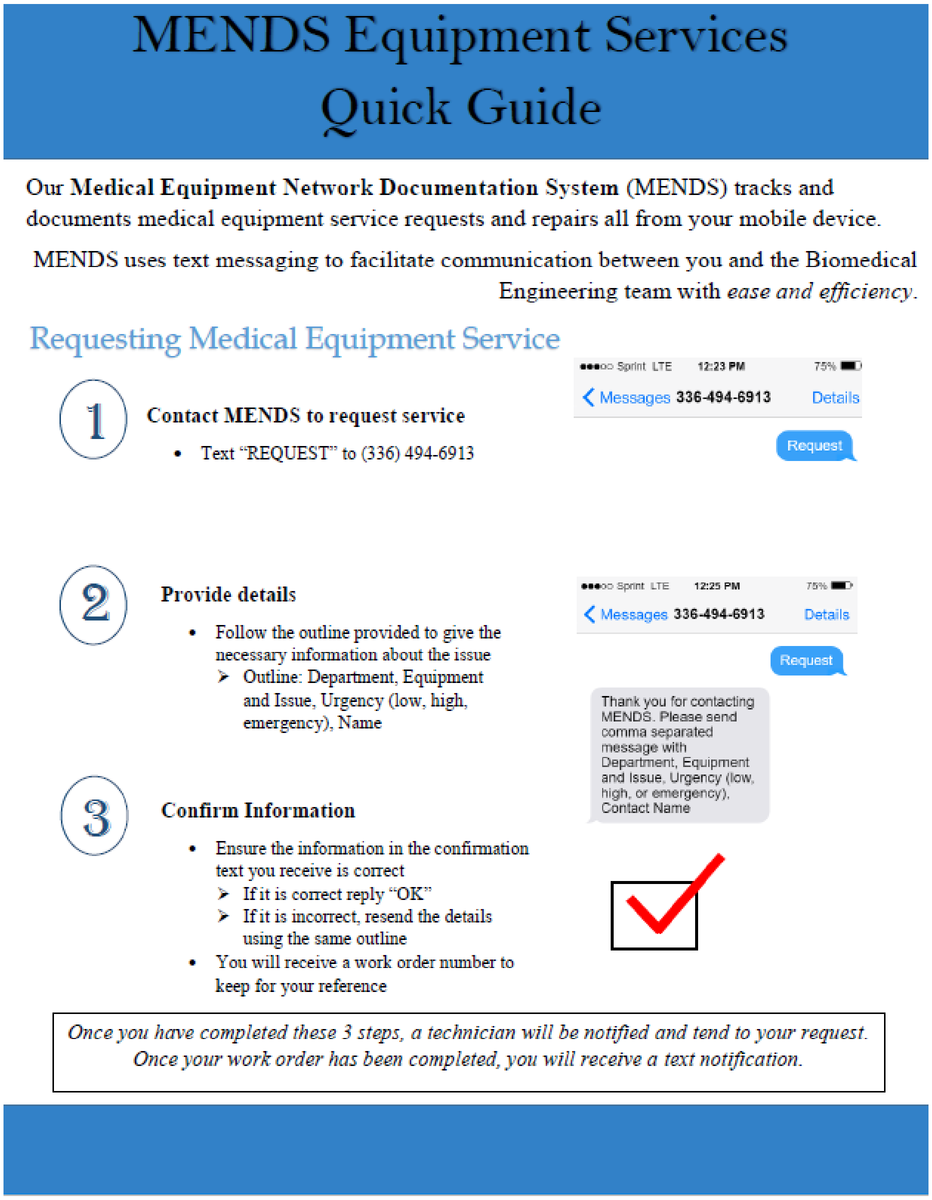

Figure 27: User Quick Guide flyer with instructions on how to use MENDS

Chapter IV: Implementation of an Automated Medical Equipment Management System for Resource Limited Settings

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ABSTRACT

Numerous resource barriers in medical facilities in the developing world contribute to equipment failures, leading to unusable equipment that disrupts patient care and drains facility finances. Suboptimal organization also contributes to equipment downtime, a situation that allows for low accountability of maintenance engineers. A strong and effective maintenance system would provide information to minimize equipment failures and extend the quality and lifespan of equipment to enhance patient outcomes. Our goal is to create a more comprehensive and organized record of equipment services and, thereby, improve communication and responsiveness. The Medical Equipment Network Documentation System (MENDS) provides a simple communication network for equipment servicing from failure to restoration using text messaging to leverage technologies in place at the point of care. The system gathers and relays information about equipment service requests and reports, and automatically saves them to an online database. MENDS was deployed in Kijabe, Kenya for a three-month pilot test. The results show MENDS more than doubles documentation and enhances ease and speed of communication. Comprehensive data provided by MENDS created more accurate measures of equipment performance, which can be used to improve turnaround time, efficiency of repairs, equipment quality, and procurement.

Keywords: Documentation, Equipment Failure, Maintenance, Point-of-Care Systems

INTRODUCTION

Nearly 80% of medical equipment in developing countries is donated from foreign sources, yet up to 70% of that equipment is unusable due to lack of resources and mismanagement [1]. Resource hindrances include lack of spare parts, tools, and manuals; lack of consumables such as single use devices; lack of trained technical staff to properly operate and maintain the equipment; and lack of reliable and continuous power and water sources [2]. These barriers contribute to equipment failures and impede proper repair, often leaving the equipment to lie unused for long periods of time. Unutilized equipment disrupts medical professionals' ability to care for their patients and can drain the facility's finances. This operating environment was studied during an intensive investigation at AIC Kijabe Hospital (KH) in Kijabe, Kenya in December 2018. KH is a 363-bed charity medical facility in a rural part of southwestern Kenya [3]. The estimated number of equipment failures experienced each month diminish the hospital's productivity and their patient's access to efficient medical care.

Mismanagement also contributes to inoperable equipment, stemming from miscommunication and disorganization during the transfer of technology to the facility and continued maintenance once there [4]. Often times maintenance plans for the equipment are loose at best; and a strong equipment management structure, with prompt procurement, deployment, and maintenance, could prolong equipment lifespan. There is currently a need for strong management structures to promote beneficial procurement and maintenance [5]. There are several key factors for an effective maintenance system including:

- Maintenance Records: Organized documentation of maintenance, including planned preventative maintenance and requested repairs.
- Availability and Quality of Documentation: Well-structured, centrally-located documentation of services and operation of equipment.
- Maintenance Reports: Regular reports on equipment status with regard to finances and staff performance [6].

Information gathered from an effective maintenance system is valuable in minimizing equipment failures, extending the quality and lifespan of the equipment, and improving procurement and donation appropriateness; all of which would have a positive impact on patient care [7], [8]. The current weak or non-existent medical equipment maintenance systems in resource-limited settings negatively impact hospital productivity and foster inappropriate use of available resources. Additionally, a strong system would improve the turnaround time of out-of-service equipment and health outcomes at these facilities.

This study focuses on the development and on-site implementation of an automated communication network for equipment servicing from failure to restoration in developing countries. The goal is to obtain a more comprehensive and organized record of equipment services and improve communication and responsiveness. This goal was achieved with the development and implementation of the Medical Equipment Network Documentation System (MENDS), a mobile device-based system that facilitates communication between equipment user and engineer while creating an ongoing digital log of comprehensive information. To ensure compatibility with developing country infrastructure, MENDS utilizes text messaging to communicate information rather than a mobile application. Only about 26% of the Kenyan population use the internet; however, 97% have mobile phones, making these the ideal platform.[9]

MATERIALS AND METHODS

Manual Method

Currently KH communicates requests for equipment service by phone call. When equipment malfunctions, users call engineers on their personal mobile phones or the Biomedical Engineering Department (Biomed) landline. The user explains the issue to the engineer who then goes to the department to tend to the request. Once the engineer completes the work, they manually record the details of the request and the service into a notebook. Those details are eventually transferred to an Excel spreadsheet to create a master log. The data logged in the Excel spreadsheet was analyzed and evaluated against the MENDS data from the pilot test, and the findings are revisited in the Results and Discussion of this study. The analysis includes evaluating user and engineer input and comparing the number of documented equipment service entries.

Alternative method. KH recently implemented a web based equipment service tracking and documenting system. Vision i-Track service portal is used to allow users to submit requests for equipment service and engineers to file reports for service completion. Users log onto the Vision i-Track website and start a new request. They fill in several details on the equipment and the issue, then submit the request. Engineers log onto Vision i-Track to see any new requests. They open the new request to see the details, then enter who will respond to the request and when. A notice is sent back to the user through Vision i-Track that is able to be seen when the user logs on. After the engineer completes the work, they log onto Vision i-Track once more and open the request. They enter a report with several details about the work completed along with a date and time. All information is saved in the system for user and engineer to see, and a log of the request and service details is printed out and stored in a binder in Biomed. This web based system is rarely used however, due to it being time consuming and inconvenient; all users and engineers revert to the phone call and manual recording method.

Concept Development

A deep investigation into the consistency issues around documentation of equipment services revealed three main challenge areas for proper equipment maintenance. These challenges include: effective communication including contacting equipment engineers, volume of repairs and the limited technological infrastructure; time management in regards to an insufficient number of equipment engineers to meet the repair volume; and accountability, where engineers are not held accountable for completing and filing maintenance reports. A device or system was needed to positively impact these challenges while utilizing the available resources. Observations and personnel input revealed that employees owned and used mobile devices throughout their workday, making it a readily available and dependable source of communication that could be leveraged.

Input from KH Biomed from multiple surveys and meetings helped determine the specific data a new system should capture as well as the ideal user criteria. The engineers expressed that a new system would be most beneficial if it contained the following features; it encompasses all necessary information, is able to access equipment history, can be used as proof of work, traces services for ease of follow up, provides alerts for any pending work, offers data showing current status of equipment, and is reliable in emergency situations.

It was determined that the minimum information needed in a service request was department name, type of machine, contact name, issue/failure type, urgency, and date. The minimum information needed in a service report was determined to be date completed, service performed, and repairman name. A cost analysis was performed to compare mobile services and to determine which would incur the least cost for the facility while performing all of the desired tasks.

System Design

MENDS was developed to capture and document equipment service requests and repairs. MENDS was adapted to function in Kenya using Africa's Talking Ltd (Lavington Nairobi, Kenya) for the short message service application programming interface (SMS API) to ensure quick, local communication. A dedicated shortcode was purchased at 11,600 Kenyan Shilling (KSH) with a 17,000 KSH per month maintenance fee ($108.95 and $159.67 respectively). The cost for MENDS to send messages to users was 0.70 KSH per outgoing message ($0.0066). Purchasing the dedicated shortcode gave MENDS two-way communication capabilities and avoided users' need to pay text messaging costs while communicating with MENDS. This cost avoidance was especially important since users would primarily be using their personal mobile devices. The information MENDS collected was backed up to an online cloud server using Digital Ocean (New York, New York) routed through Bangalore, India. This created an ongoing, continuously updated database.

MENDS' operation is briefly described in its three functions: requesting, assigning, and reporting. The flow of the process is seen in Figure 28.

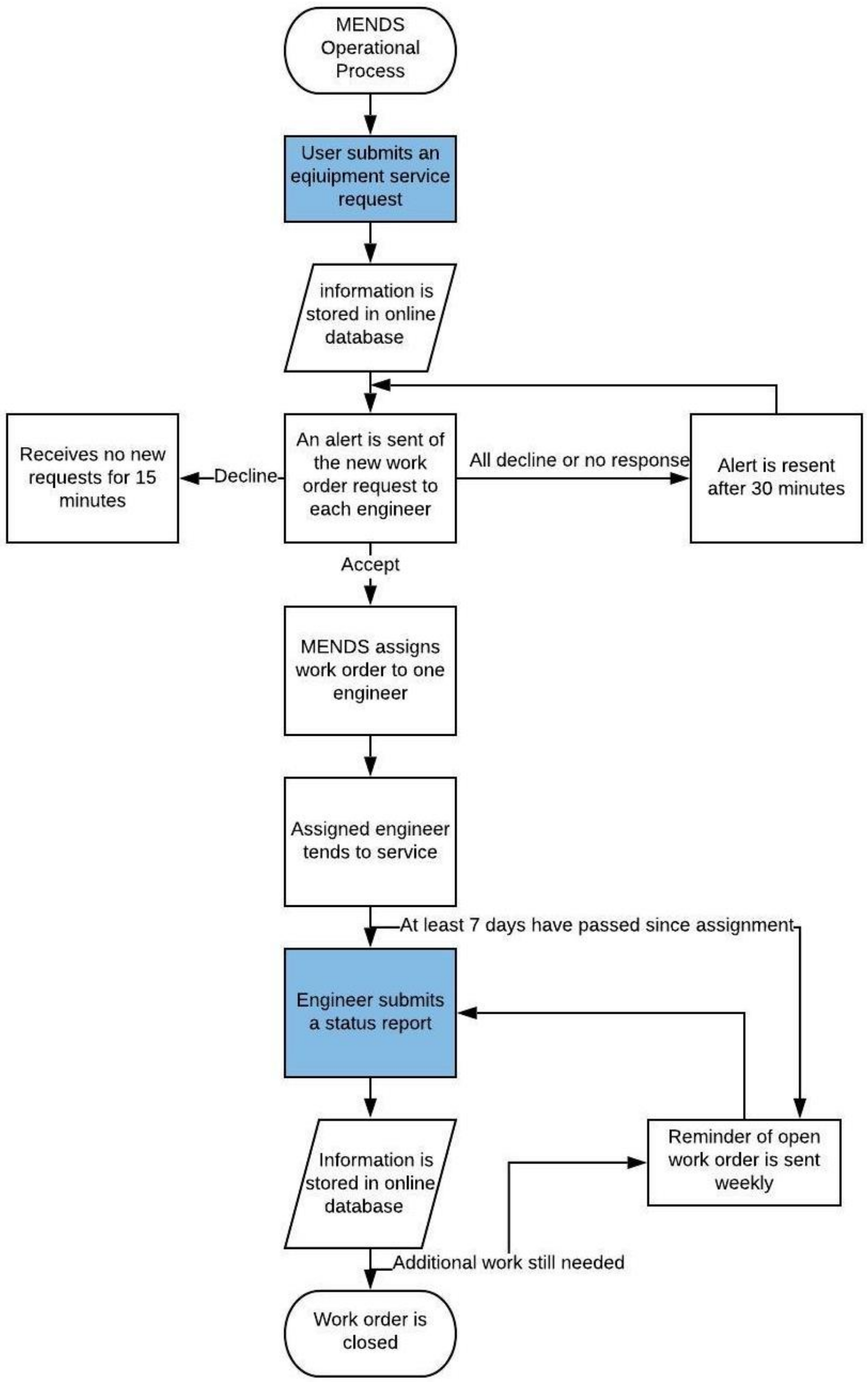

Figure 28: Flowchart of MENDS (Medical Equipment Network Documentation System) operation and information.

When equipment malfunctions, equipment users submit a request for service via text message to MENDS, including the equipment type, department location, specific equipment issue, urgency, and user's name. MENDS sends a response to the user, restating the submission details for user verification. Once verified, the information of the request is saved to the online database. MENDS then sends a text alert to each engineer to inform them of the details of the request and to ask them to either accept or decline the work order. The engineers have five minutes following the alert to respond. After five minutes, MENDS assigns the work order to one of the accepting engineers. Assignment selection is based on engineer's availability and number of outstanding work orders to ensure work is distributed equitably. The assigned engineer is responsible for managing the service and completing a status report.

Engineers are responsible for contacting MENDS when work is complete via text message, detailing the work order number, description of the work completed, cost associated with the service, need for additional work on the equipment, and stipulations on the use of the equipment. MENDS sends a response to the engineer restating the submission details for verification. Once verified, the report information is saved in the online database, and the work order is closed. Weekly reminders are sent to each engineer with the number of the work orders that are open. An example of the text message conversation is in Figure 29. This design was tested in Winston Salem, North Carolina at Wake Forest Baptist Medical Center (WFBMC) to ensure the system worked as intended and to optimize its functionality.

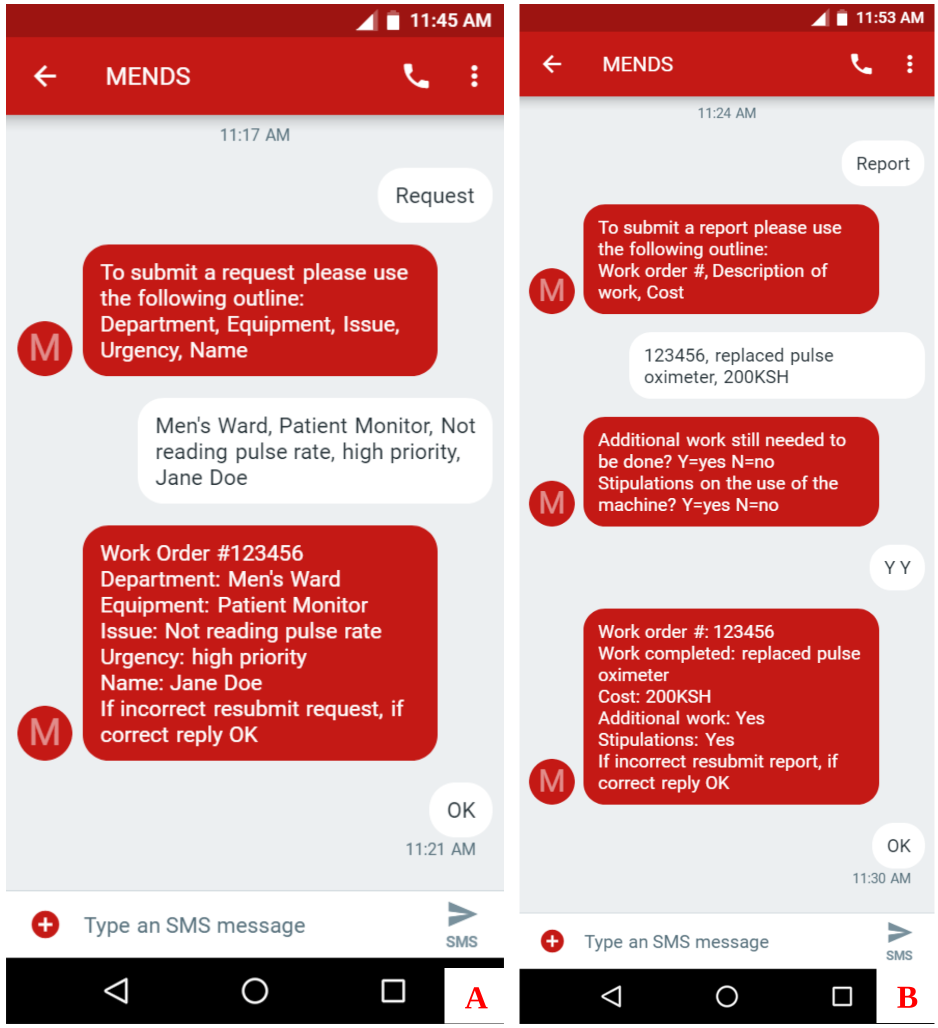

Figure 29: Text message conversations with MENDS. A) user requesting service, and B) engineer reporting service.

Testing Method

Testing of MENDS was performed by deployment and pilot usage at KH. Prior to receiving instruction on using MENDS, each participant was asked to complete a survey to obtain their opinion on the current manual equipment maintenance documentation method. The survey shown in Figure 30A was given to equipment users, and the survey in Figure 30B was given to engineers.

SCAN ME

Current Repair Request System User Evaluation Survey

Name: *Department:*

Phone: *Email:*

1. What is your current method of requesting equipment repair? (Check all that apply)

☐ Submit request online
☐ Call engineer
☐ Other:

2. Rate the current method of requesting equipment service on a scale of 1-5 based on the following criteria: (circle one number for each criteria)

5 = strongly agree	4 = agree	3 = neutral	2 = disagree	1 = strongly disagree
Overall, I am satisfied with the current system				5 4 3 2 1
The current system is easy to use				5 4 3 2 1
I am able to quickly request equipment service				5 4 3 2 1
I am able to effectively submit a request for equipment service				5 4 3 2 1
It was easy to learn how to use the current system				5 4 3 2 1
The current system is efficient				5 4 3 2 1
I feel comfortable using the current system				5 4 3 2 1

3. How often do you make requests? (Check only one)

☐ Never
☐ Sometimes (once or twice a month)
☐ Often (several times a month)
☐ Always (whenever a repair is needed)

4. What are the issues with the current system?

5. What are the advantages of the current system?

6. Additional comments:

A

SCAN ME

Current Repair Request System Engineer Evaluation Survey

Name: *Department:*

Phone: *Email:*

1. What is your current method of receiving equipment service requests? (check all that apply)

☐ View request online
☐ Receive a call
☐ Other:

2. What is your current method of reporting equipment repair? (Check all that apply)

☐ Submit report online
☐ Manually type in on computer
☐ Handwritten
☐ Other:

3. Rate the current method of tracking equipment service on a scale of 1-5 based on the following criteria: (circle one number for each criteria)

5 = strongly agree	4 = agree	3 = neutral	2 = disagree	1 = strongly disagree
Overall, I am satisfied with the current system				5 4 3 2 1
The current system is easy to use				5 4 3 2 1
I am able to easily receive new equipment service requests				5 4 3 2 1
New service requests are assigned quickly and fairly				5 4 3 2 1
I am able to quickly report equipment service				5 4 3 2 1
I am able to effectively submit a report for equipment service				5 4 3 2 1
It was easy to learn how to use the current system				5 4 3 2 1
The current system is efficient				5 4 3 2 1
I feel comfortable using the current system				5 4 3 2 1

4. How often do you submit reports? (Check only one)

☐ Never
☐ Sometimes
☐ Often
☐ Always

5. What are the issues with the current system?

6. What are the advantages of the current system?

7. Additional comments:

B

Figure 30: Manual equipment maintenance system evaluation survey. A) for users, and B) for engineers.

Next, key personnel in each participating department received in person instruction on how to use MENDS and how to locate further support resources if necessary. The engineers received more in depth training on operating MENDS both as a user and as an engineer. Following the survey and presentation, each user and engineer was instructed to test MENDS on their personal devices. They were guided through the process and all questions were answered to ensure successful repetition throughout the testing period. Engineers were instructed to:

1. Save the dedicated shortcode in their contacts as MENDS.

2. Register their number with MENDS by texting “Register, 6242019, Your Name” to the shortcode.
3. Text the word “Report” to MENDS.
4. Follow the outline provided in MENDS’ reply to text a fictional report.
5. Read over the confirmation message in MENDS reply.

All users were instructed to:

1. Save the dedicated shortcode in their contacts as MENDS.
2. Text the word “Request” to MENDS.
3. Follow the outline provided in MENDS’ reply to text a fictional request.
4. Read over the confirmation message in MENDS reply.

The instructional period lasted for three days, with visits to each department. MENDS then went live at KH, and five additional days were allocated for troubleshooting. The pilot test ran for three months, February 2020 through April 2020, and included the following departments: Outpatient (OPD), Casualty (emergency), Pediatrics, Dental, Theatre (operating rooms), Intensive Care Unit (ICU), Satellite Clinics, Inpatient Wards, Maternity Ward, and Laboratory (Lab). Afterward, users and engineers were again surveyed using the tool in Figure 30 but in reference to their experience with MENDS.

RESULTS

Survey Results

The pre and post pilot test surveys (Figure 30) were administered to 24 users and five engineers. Both surveys were returned from seven users and four engineers. Figure

31 shows the responses to the statement, “Overall, I am satisfied with the system.” Eight of eleven surveyed participants specified either a neutral response or disagreement with the satisfaction statement regarding the manual method. Ten of eleven surveyed participants whose original satisfaction responses regarding the manual method were disagree, neutral, or agree, communicated greater satisfaction with MENDS by strongly agreeing with the statement.

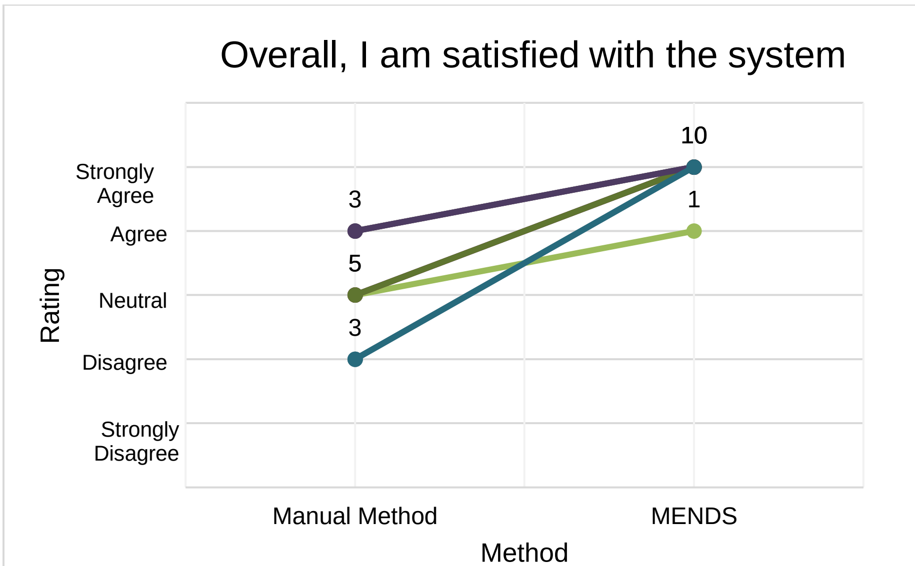

Figure 31: User and engineer rating for overall satisfaction with each documentation system; numbers above the points indicate the number of participants and the lines indicate the participant’s change in rating from the manual method to MENDS.

Table 7 displays average ratings and percent increase in the rating from the manual method to MENDS for the remainder of the statements in the pre and post-test surveys from the users. The rating scale is from a minimum of 1 – strongly disagree, to a maximum of 5 – strongly agree. Ratings were 4.9 or higher when pertaining to statements about MENDS, while statements pertaining to the manual method received its highest rating of 3.9 in reference to the statement “The system is easy to use.” All responses showed an average of at least 30% increase in rating, with comfort of use having the greatest increase at 108%.

Table 7: Average ratings and percent increase in rating from the manual method to MENDS (Medical Equipment Network Documentation System) for each statement in the pre and post-test survey given to users.

User	**Average Rating (out of 5)**		
	Manual Method	MENDS	Percent Increase
Overall, I am satisfied with the system	3.1	5.0	73%
The system is easy to use	3.9	5.0	31%
I am able to quickly request equipment service	3.6	4.9	45%
I am able to effectively submit a request for equipment service	3.1	5.0	79%
It was easy to learn how to use the system	3.7	5.0	37%
The system is efficient	3.3	5.0	69%
I feel comfortable using the system	3.0	5.0	108%

Table 8 displays average ratings and percent increase in the rating from the manual method to MENDS for the remainder of the statements in the pre and post-test surveys from the engineers. Ratings were 4.5 or higher when pertaining to statements about MENDS, while statements pertaining to the manual method peaked at 3.5 for ability to quickly report services. All responses showed an average of at least 40% increase in rating, with system efficiency having the greatest increase at 90%.

Table 8: Average ratings and percent increase in rating from the manual method to MENDS for each statement in the pre and post-test survey given to engineers.

Engineer	**Average Rating (out of 5)**		
	Manual Method	MENDS	Percent Increase
Overall, I am satisfied with the system	2.8	4.8	79%
The system is easy to use	3.0	5.0	77%
I am able to easily receive new equipment service requests	3.0	5.0	88%
New service requests are assigned quickly and fairly	3.0	4.8	71%
I am able to quickly report equipment service	3.5	5.0	46%
I am able to effectively submit a report for equipment service	2.8	5.0	88%
It was easy to learn how to use the system	3.3	4.5	54%
The system is efficient	2.8	4.8	90%
I feel comfortable using the system	3.0	4.8	69%

Table 9 lists the overall themes of the advantages and disadvantages for each system from the free text comments conveyed by participants on the surveys. A complete list of comments can be seen in Appendix F. Many of the disadvantages with the manual method, such as responsiveness, recordkeeping, ownership, and efficiency of requesting and reporting, were advantages for MENDS.

Table 9: Free text comments on pre and post-test surveys from users and engineers for the manual method and MENDS.

Manual Method	*MENDS*
Advantages	
• Direct contact with engineers	• Easy to contact engineers and quick response • Quick, simple, and easy request and report submission • Comprehensive records • Efficient ownership
Disadvantages	
• Difficulty contacting engineer and delay in response • Lack of records • Poor ownership and accountability • Inefficient request and report submission	• Difficulty to quickly learn how to use • Incorrectly used

It should be noted that 18 out of 27 persons trained to use MENDS completed at least one request or report, yielding a 66% adoption rate. More than 50 people in the participating departments who did not receive official formal training were able to learn and use MENDS over the course of the three-month testing period.

Equipment Maintenance Results

Figure 32 displays the total number of equipment service entries documented, including completed and open work orders, for the manual method and MENDS. Documentation is from February through April for the manual method in 2018 and 2019 and for MENDS in 2020. The trend is consistent across each method and year with an increase in entries from February to March followed by an acute decline from March to

April. MENDS, however, chronicles more than twice as many entries per month than the manual method.

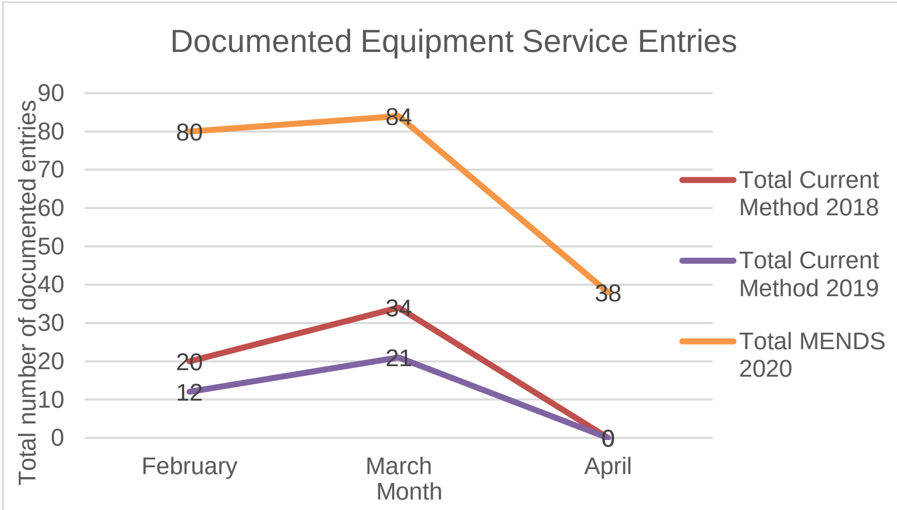

Figure 32: Number of documented equipment service entries using the manual method in 2018 and 2019 versus MENDS in 2020 across the three-month period.

From the data collected using MENDS, several characteristics of equipment maintenance and performance were able to be measured. All measurements include completed and open work orders. Figure 33 shows the failure rate of equipment per department while using MENDS. Failure rate is the probability per time that the department experiences equipment failure throughout the testing period. The equation for failure rate is:

$$\text{Failure Rate} = \textit{Number of failures}/\textit{Total test period time}(3 \text{ months})$$

The highest failure rate was in the ICU and Theatre departments, showing over 0.6 failures per day.

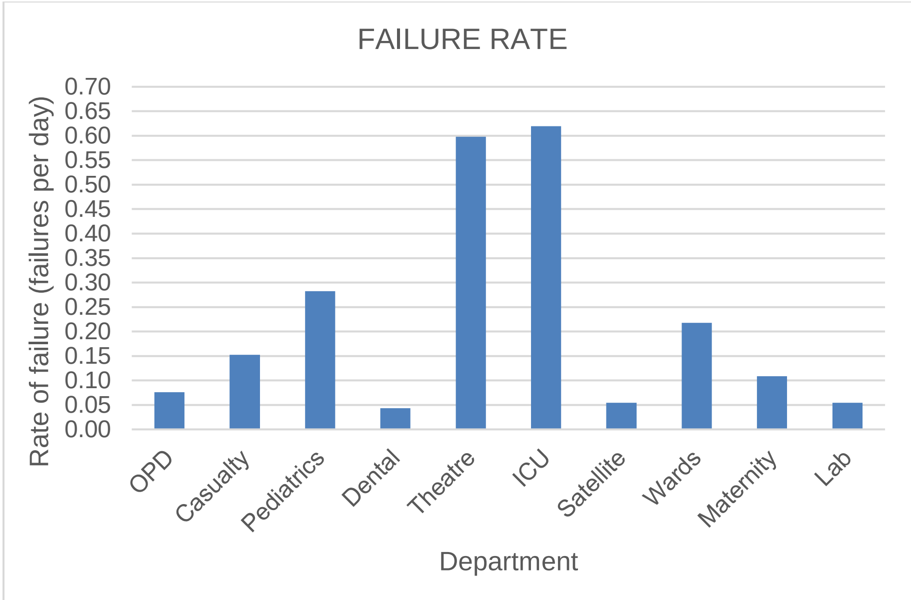

Figure 33: The equipment failure rate in each department using MENDS within the three-month testing period.

Figure 34 illustrates operational availability of the departments as the probability that the equipment in the department will operate satisfactorily at a given point in time within the testing period. The equation for operational availability is:

Operational Availability = [*Uptime* (total time equipment was operational/*Operating Cycle* (3 months)]x100%

The departments with the highest operational availability was OPD and Maternity at almost 80% and 70%, respectively. All other departments were at less than 50% operational availability.

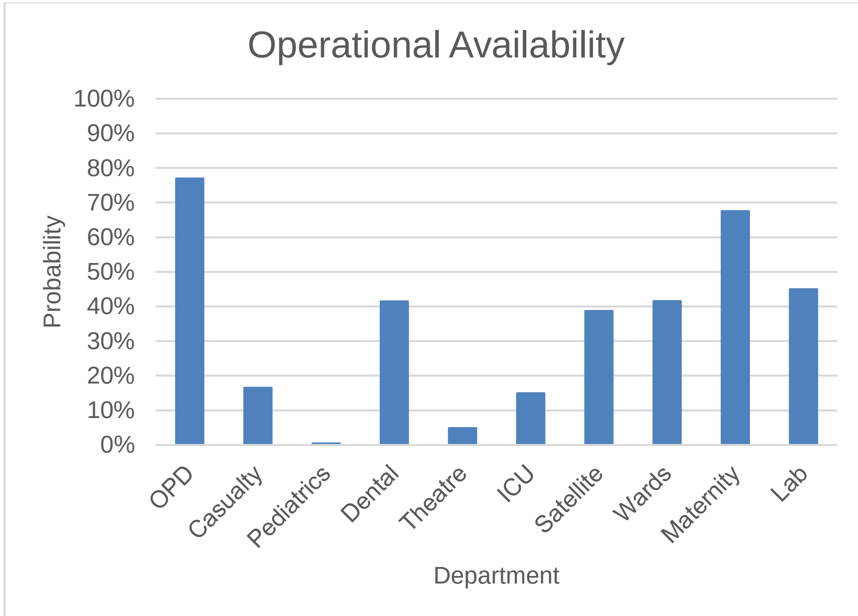

Figure 34: The operational availability in each department when using MENDS as the probability that the equipment in the department will operate satisfactorily at a given point in time within the testing period.

Figure 35 shows the resolution time of each service in each department over the testing period. Time is specified in days; 10^{-2} days ~15 minutes, 10^{-1} days ~ 2.5 hours, 10^{0} days=1 day. Table 10 shows the results of the one-way ANOVA for the resolution times between departments. Resolution time is the time from the submission of a service request to the submission of its corresponding report. There is a wide variety of resolution times in each department with the shortest being less than 10 minutes and the longest being more than 10 days. However, with a p-value of 0.08, there is no significant difference in resolution time between departments.

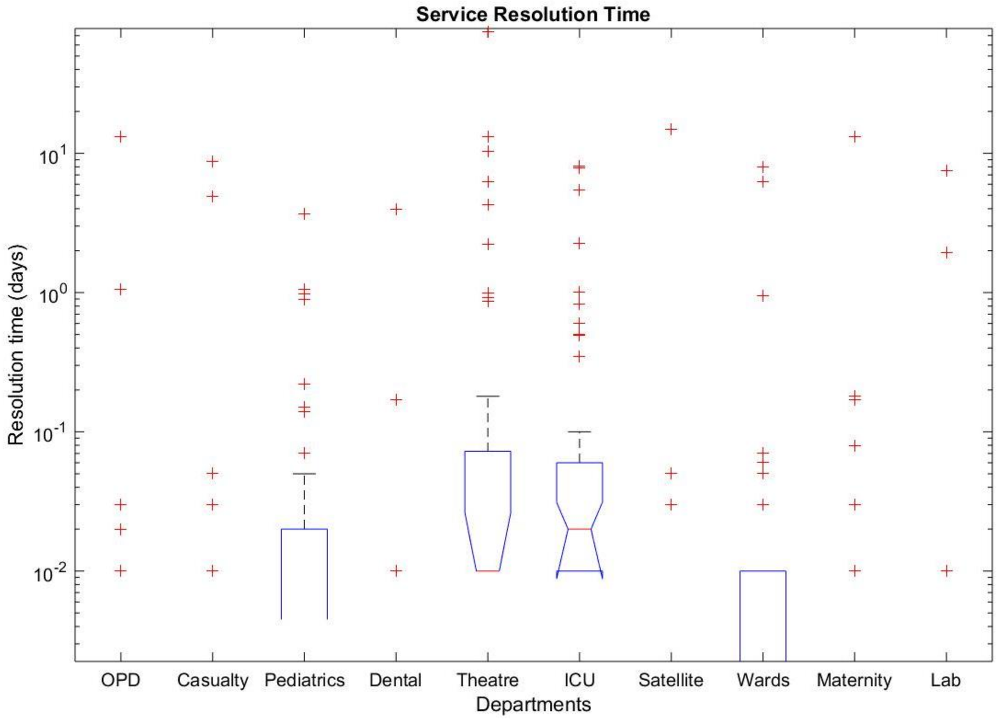

Figure 35: Resolution time of services (time from submission of request to the submission of its corresponding report) in each department when using MENDS within the three-month testing period.

Table 10: One-way Analysis of Variance for service resolution time (time from submission of request to submission of its corresponding report) between departments while using MENDS.

Source	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F**	**Sig (α=0.05)**
Columns	220.39	9	24.49	1.75	NS[1]
Error	6707.74	480	13.97		
Total	6928.13	489			

[1]P-value 0.08> 0.05, not significant

DISCUSSION

The manual equipment maintenance method was varied and unpredictable; as a result, it was necessary to rely heavily on qualitative data from participant surveys in order to evaluate the effect on communication. The records from using the manual method were deemed unreliable for several reasons. A significant increase of equipment service entries was documented when using MENDS versus the manual method. This finding suggests the manual method under-recorded equipment services. Under the manual method, there was no documentation for open work orders, meaning all documentation was carried out on completed work orders only. The timestamps documented on each entry using the manual method may be incorrect because; they were manually documented, information about the request and the completion report were documented simultaneously when the work was completed, several entries showed the completion report dated earlier than the request – in these cases it was assumed the times were transposed, and for several entries the request and completion report time/date were recorded as the same.

It is important to note that participant input is crucial to determining the success of MENDS. The input and opinion of the users and the engineers as to the benefit and ease of using a new system speaks to their readiness to adopt it. Without their participation and endorsement, a new method will be useless despite its many strengths.

Survey Results

The survey results in Figure 31, Table 7, and

Table 8 suggest there is a gap in effective communication when using the manual method. Participants gave satisfaction ratings of mainly neutral, and at times lower, for the survey statements. In contrast, 100% of the surveyed participants gave MENDS a rating of agree or strongly agree for every survey statement regarding utility and usability. All participants increased their rating for every statement from the pre-test survey to the post-test survey. This is a strong indication that MENDS is able to bridge the gap created by the manual method. The survey results confirm MENDS's ability to make the communication process for equipment service requesting, assigning, and reporting quick, efficient and effective. MENDS is seen as a faster method and is easy to learn, and participants felt comfortable using it as their form of communicating equipment needs.

Comments in Table 9 further support MENDS as a viable tool for communication and documentation. Personnel expressed MENDS effectively contacted engineers, improved response time, and provided needed follow-up. MENDS improved accountability and ownership among the engineers while being simple, easy, and timesaving. The more than 50 personnel within the departments who did not receive formal training were able to easily and correctly use MENDS, demonstrating MENDS is user friendly. According to personnel at KH, the manual method caused delays in response from engineers, difficulty in contacting engineers, and encouraged little follow-up from engineers. Although some users appreciated the ability to speak directly to an engineer, they expressed the direct conversation did little to improve accountability and ownership among the engineers.

Equipment Maintenance Results

As captured in Figure 32, MENDS resulted in a substantial increase in the number of equipment services documented. There were four times more entries in February, about two and a half times more in March, and 38 entries versus the zero collected using the manual method in April. This confirms successful communication, service completion, and documentation using MENDS. However, the consistent fluctuation in number of entries from February to March and March to April across methods highlights a need to evaluate other factors. Further investigation into influences such as environmental factors, staffing, equipment usage, planned preventative maintenance schedule, and practiced procedures may help determine the cause of the oscillation every year.

MENDS gives a more accurate depiction of the performance and maintenance of equipment in each department at KH. Figure 33, Figure 34, and Figure 35 reveal the unreliable nature of the equipment. Precise failure rate measurements were calculated showing several departments were often in a state of failure, and most departments were running at less than 50% probability of equipment being operational when desired. In Figure 35, common issues were identified among services with the longest and shortest resolution times. Longer resolution times often stemmed from a need to obtain the equipment manual or to travel to obtain spare parts. These processes are known to cause significant delays. The shorter resolution times occurred when equipment was not broken but simply needed a service, such as refilling oxygen tanks or repositioning equipment; both of which can be done quickly and onsite. Overall, the data received from MENDS more accurately aligns with the testimonies and observations made at the hospital and with published work on the condition of medical equipment in resource-limited settings.

This study had several limitations in addition to the variable data obtained from manually built records. First, a few participants incorrectly texted when sending information to MENDS. Secondly, it was impossible to track individual equipment due to a lack of an existing labeling system. For example, KH has multiple ventilators but they cannot be individually tracked. Third, the dedicated shortcode cost is per mobile network, so we only paid for connectivity with Safaricom PLC (Nairobi, Kenya) since most personnel at KH were in service with Safaricom. Therefore, only users with Safaricom mobile plans were able to communicate with MENDS. Also, the cost for the pilot test was covered by the research team, necessitating a three-month window to gather data. Finally, the 2019 Coronavirus Disease pandemic began in Africa in the middle of this study. KH had to adapt its service to the infectious disease environment, which altered its use of equipment and its serving needs. Moreover, travel to Kijabe to end the pilot test in person was rescinded.

CONCLUSION

Data collected from the three-month pilot test, pre and post-test surveys, additional written documentation from participants, and first-hand observations all indicate that MENDS successfully met the study goal. MENDS provided a user-friendly, adaptable platform that improved communication by increasing ease and speed, as well as increased quantity and quality of documentation. The consistent and accurate data allowed for supplementary measurements to analyze equipment performance. Although the manual method bares little to no cost on the facility while MENDS operates at about 234,000 KSH per year ($2,200), the ability to capture a higher quantity and quality of data gives greater long term savings. These benefits include the ability to monitor equipment to predict when it will need replacement, increased efficiency of repairs for engineers, and decreased resolution time, returning equipment to service and increasing patient care and throughput. MENDS provides evidence necessary to predict when current devices are end-of-life so the facility can plan for purchases or better inform potential donors about needed equipment types. Further improvements to MENDS include minimizing cost of operation by sharing the dedicated shortcode among multiple hospitals. Improvements also include incorporating a preventative maintenance schedule and creating an equipment inventory database, with tracking of individual items, particularly the more expensive ones. The end result is a system to lower overall costs for equipment and to repair equipment quickly and efficiently, thereby allowing these important medical facilities to meet the healthcare needs of the local population.

CONTRIBUTIONS

RMG, PJB, FSG, and EYA conceived the study; RMG and SGS designed and developed the system; RMG, SGS, and EYA carried out the onsite deployment; RMG, PJB, and FSG carried out the analysis and interpretation of the data; RMG drafted the manuscript; All authors critically revised the manuscript for intellectual content, and read and approved the final manuscript.

ACKNOWLEDGEMENTS

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FUNDING

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COMPETING INTERESTS

None declared.

ETHICAL APPROVAL

Not required.

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APPENDIX

Appendix F: Free text comments on pre and posttest surveys from users and engineers

Table 11: Free text comments in pre and posttest survey from users and engineers.

Current Method	MENDS
• Delay in response from the engineers • Phone calls are forgotten – you have to call several times • The repairs needed are mostly not documented and work done isn't also • You can call at any time for repairs to be done • The request may or may not be effective depending on the person requesting • No classification of emergencies • No datasheet to show status of equipment • Direct on call • Forgetting to report and record; proper details missing; handwritten is very tiresome • Slow; some work left undone • Some records are kept • No accountability or traceability of request • You talk directly to biomed • Poor ownership • Sometimes calling and no answer; not able to get the engineer when needed and no good reference • You talk to an individual person	• It is an easy method to contact any engineer • I highly recommend MENDS in any medical facility because it makes it easier to contact the engineer/biomed team • It is quick to notify biomed about repairs, saves time • It is a brilliant idea and technology to aide healthcare workers on equipment servicing • Quick response and ease of use • Quick service for ordering and submitting the work report • Some use it for the wrong purpose and they find it difficult to quickly learn how to use it • Simple to use, easy to submit report and see what work has been done during the month or even the year • Fast; easy to fill anywhere, anytime; keeps records • Makes work easier • Efficient ownership of assigned job • Efficient, simpler, easy and effective • Efficient, not time consuming

Chapter V: Summary of Research

The research completed in this thesis was in support of bridging the gap in healthcare disparity among developed and developing countries. A large portion of the inequality is due to the suitability, management, and maintenance of the medical equipment. Therefore, a robust, automated communication and documentation system for medical equipment servicing was developed and tested. The Medical Equipment Network Documentation System (MENDS) coordinates and records medical equipment service request and reports from a mobile device using text messaging. The initial testing in Winston Salem, NC allowed for optimization and comparison to the effectiveness of developed country methods.

The onsite testing in Kijabe, Kenya confirmed MENDS' usefulness and efficiency. All participants in the study agreed that it improved responsiveness of equipment engineers and increased the speed and ease of communicating requests and reports. The over 200% increase in documented equipment service entries verified MENDS' ability to improve recordkeeping. The comprehensiveness of the records allowed for a more accurate depiction of equipment maintenance and performance which is essential to the upkeep of the equipment and finances of the facility. The information and consistency that MENDS brings enhances patient health outcomes in developing countries to improve health equity around the globe. Research presented in Chapter III has been published, and research in Chapter IV has been submitted to a scientific journal. Information is listed in Table 12.

Table 12: Publication of research in thesis

Chapter	Title	Journal
III	Mobile Documentation System for Medical Equipment Servicing in Developing Countries	Biomedical Sciences Instrumentation *
IV	Implementation of an Automated Medical Equipment Management System for Resource Limited Settings	International Health +

*Published
+Submitted

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PROFESSIONALSUMMARY

Years of hands on experience in the medical device field successfully developing, designing, and improving new and currently marketed medical devices and processes for surgical aide, at home care, and resource-limited facilities. Used learned communication and leadership skills to cultivate relationships with multidisciplinary partners in order to lead and manage multiple projects in several parts of the United States and Kenya. Experienced in applying the design process to translate consumer needs into products as well as engaging with stakeholders. Areas of experience include:

- Cell Culturing
- Tensile Testing
- Medical Imaging Physics
- Six Sigma Green Belt (2017)
- Data Analysis and Interpretation
- CAD and Statistical Software
- Communicating Science

EDUCATION

Virginia Tech - Wake Forest University, Winston Salem, NC — Expected Graduation: August 2020
Master of Science in Biomedical Engineering — **GPA: 3.65**

North Carolina A&T State University, Greensboro, NC — Graduated: May 2018
Bachelor of Science in BioEngineering with a minor in Public Relations — **GPA: 3.98**

PROFESSIONAL EXPERIENCE

Research Associate, Virginia Tech-Wake Forest Center for Injury Biomechanics, Winston Salem, NC
(PI: Dr. F. Scott Gayzik and Dr. Philip J. Brown) **August 2018 – Present**

- Collaborate with technical and medical professionals in multiple countries to create a novel mobile system to enhance medical equipment efficiency, productivity, and documentation in deprived medical facilities around the world.
- Coordinated and analyzed the successful implementation of the developed system in sub-Saharan Africa to evaluate its systematic and financial ability to be transferred globally.

Research Intern, Naval Research Laboratory, Washington, DC May 2017 – August 2017

- Successfully developed a closed system for reading neuronal action potential with a team of six as a precursor for developing automated systems that respond to scent.
- Designed and 3D printed various microscopic devices as well as achieved cell culturing.

Engineering Intern, Cook Medical Inc., Bloomington, IN August 2016 – December 2016

- Contributed to redesigning faulty catheters by brainstorming process, material, and packaging solutions and writing protocols, reports, and other documents for various quality testing conducted by myself or other team members.
- Procured age and exposure testing for catheters with Singota Solutions.

LEADERSHIP & ACTIVITIES

- *Member*, Black Graduate Student Association, Winston Salem, NC	November 2019 – Present
- *Head Mentor*, Leaders in Training, Winston Salem, NC	October 2019 – Present
- *Captain/Secretary*, Wake Forest University Gymnastics Club, Winston Salem, NC	August 2019 – Present
- *Scholar*, Scientist Mentoring & Diversity Program for Medical Technology	August 2019 – Present
- *Gymnast*, Wake Forest University Gymnastics Club, Winston Salem, NC	August 2018 – Present
- *Outreach Chairperson*, Mt. Nebo Youth Department, Blackstone, VA	January 2017 – Present
- *Member*, National Society of Black Engineers, National Member	August 2015 – Present
- *Member*, Biomedical Engineering Society, National Member	August 2014 – Present

AWARDS AND ACCOMPLISHMENTS

- Tau Beta Pi Engineering Honor Society
- Phi Kappa Phi Honor Society
- Wake Forest Alumni Student Travel Award ($300)
- Masters student tuition scholarship ($25,740/year)
- Center for Creative Leadership Certification (2016)
- Phi Kappa Phi Love of Learning Award ($500)
- NCAT Dowdy Scholar Full Scholarship (1 of 20)
- BB&T Emerging Leaders Certification (2017)

JOURNAL PUBLICATIONS

1. Gordon R., Saldaña S., Brown P.J., Gayzik F.S., Anthony E. “Implementation of an Automated Medical Equipment Management System for Resource Limited Settings.” *International Health*. June 2020. Submitted
2. Gordon R., Saldana S., Brown P.J., Gayzik F.S., Anthony E. Mobile Documentation System for Medical Equipment Servicing in Developing Countries. *Biomedical Sciences Instrumentation*. Apr 2020;56(2):392-401.

PRESENTATIONS

1. Gordon R., Saldaña S., Brown P.J., Gayzik F.S., Anthony E. [Poster] “Mobile Documentation Systemfor Medical Equipment Servicing in Developing Countries.” *2020 Graduate Student and Post Doc Research Day.* Virtual, April 10, 2020
2. Gordon R., Saldaña S., Brown P.J., Gayzik F.S., Anthony E. [Poster] “Mobile Documentation System for Medical Equipment Servicing in Developing Countries.” *2019 BMES Annual Meeting.* Philadelphia, PA, October 17, 2019
3. Gordon R., Brown P.J., Gayzik F.S., Anthony E. [Poster] “Medical Process And Equipment Solutions In Rural And Remote Developing Countries.” *SBES Symposium 2019.* Blacksburg, VA, May 15, 2019

PROFESSIONAL WORKSHOPS

1. Department of Defense Radioactive Material Training Session February 18, 2019