THE PARTOPEN: USING DIGITAL PEN TECHNOLOGY TO IMPROVE MATERNAL LABOR MONITORING IN THE DEVELOPING WORLD

by

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ABSTRACT

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The PartoPen: Using Digital Pen Technology to Improve Maternal Labor Monitoring in the Developing World

Directed by Professor John K. Bennett and Sarah Revi Sterling

This dissertation presents the PartoPen, a new approach to addressing maternal labor monitoring challenges in developing countries. The PartoPen is a hardware and software system that uses digital pen technology to enhance, rather than replace, the paper-based labor monitoring tool known as the partograph. In the developing world, correct use of the partograph form to monitor the progress of maternal labor has been shown to reduce the number of obstructed labors, and consequently, the number of maternal deaths and stillbirths. However, previous work over the last decade has shown that there are several barriers to both partograph completion, and to correct use of the partograph form. Inadequate training and lack of ongoing education regarding partograph use are among the most significant of these barriers.

The PartoPen seeks to address these barriers by adding interactivity to the partograph in the form of audio instructions, decision-support, and patient-specific reminders. The design of the PartoPen system is based on the hypotheses that (1) audio instructions accessible via tapping the digital pen to the paper partograph will reinforce nurse training and promote partograph completion; (2) real-time decision support will reduce data interpretation errors and promote timely decision-making regarding patient care; and (3) time-based patient-specific reminders will promote ongoing and timely delivery of patient care.

This dissertation describes the design, implementation and evaluation of the PartoPen system in teaching and clinical settings in Nairobi, Kenya. The results of four PartoPen studies,

conducted both in nursing classrooms and in labor wards, were used to evaluate the system and refine its design. At the University of Nairobi, nursing students using the PartoPen as a training tool were able to correctly perform controlled partograph completion tasks with minimal or no training on PartoPen use. PartoPens deployed in the labor ward at Kenyatta National Hospital were successfully used and sustained for nine-months of continuous hospital use. Finally, results from the PartoPen system evaluation also provide significant guidance for future work using digital pen systems for healthcare applications in developing countries.

To my parents, who have given me a life of love and learning.

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1. INTRODUCTION

The World Health Organization (WHO) estimates that 300,000 women die every year due to pregnancy-related complications, most of which occur in developing countries [1]. Timely and informed labor monitoring by a skilled attendant can help prevent many of the main causes of maternal death – hemorrhage, infection, unsafe abortion, eclampsia, and obstructed labor [2]. Globally, the WHO promotes the paper partograph as an effective and cost-efficient tool for monitoring labor, and preventing obstructed labor and resulting complications. Used correctly, the partograph provides decision support that assists in early detection of maternal and fetal complications during labor. Especially in rural clinics, early detection allows transport decisions to be made in time for a woman to reach a regional facility capable of performing emergency obstetric procedures.

Despite the positive reports of improved maternal outcomes resulting from correct partograph use [3]-[5], several recent studies in Kenya have reported underuse and incorrect use of the partograph at all levels of maternity care [6]-[8]. The well-documented barriers to partograph use include resource shortages, understaffing, inadequate partograph knowledge and training, and the perspective of some that the partograph is time consuming and redundant [6]. The goal of the PartoPen project is to mitigate some of these barriers to partograph adoption and correct use via an interactive digital pen, dedicated pen software, and partograph forms printed with a background dot pattern that is recognized by the pen. Using only the digital pen and the existing paper form, the PartoPen addresses training and resource barriers by providing audio-based decision support, patient-specific reminders, and partograph use instructions.

1.1 Development and Use of the Partograph for Maternal Labor Monitoring

Emmanuel Friedman first conceptualized what would later become the 'partograph' in 1954, when he determined that the rate of cervical dilation versus time was highly consistent among birthing women [9]. This discovery led to the creation of standardized S-curves representing the progression of normal, uncomplicated labors. In 1972 R. H. Philpott, a professor of obstetrics and gynecology at the University of Rhodesia (now Zimbabwe), used these S-curves to create a graphical, real-time decision support tool that allowed birth attendants to monitor cervical dilation over time, plot those measurements on the graph, and determine if labor was progressing normally or abnormally [10]. Philpott and his colleague, W. M. Castle, added other components to the partograph in addition to the cervical dilation graph providing a more comprehensive evaluation of the health of the mother and child during labor. These components included fetal heart rate, molding of the fetal skull bones, amniotic fluid color, contraction patterns, blood pressure, pulse, temperature, and urine output [10]. Initial studies in Zimbabwe showed that use of the partograph resulted in a significant decrease in prolonged or obstructed labor cases and an improvement in neonatal outcome [10].

The evaluations of the partograph in Zimbabwe raised questions about possible race-related differences in "normal" labor rates. The partograph had also been adopted by several clinics in the UK yet there was no comprehensive study done in the UK on the affects of the partograph on clinical outcomes. In response to these concerns John Studd, a professor in the UK, conducted a study in 1973 evaluating the use of Philpott's partograph during 15,000 labors in the UK [11]. The results of Studd's trial indicate that the partograph, and particularly, the action lines on the cervicograph (a graph of the cervical dilation on the partograph), help identify prolonged labors and "high-risk" patients in the UK as well as in Zimbabwe. At the conclusion

of Studd's trial, over half of the clinics in the UK were using the partograph during all labors and deliveries. The partograph is still widely used in England today, but comes in a variety of formats and is used to varying degrees [12]. However, the partograph is not widely used in other developed countries, such as the United States and Turkey where maternal outcomes are generally positive, most likely because of the availability of emergency care procedures and the effective use of other types of labor monitoring strategies (e.g., electronic fetal monitoring) [13].

1.2 Reducing Maternal Mortality and Morbidity using the Partograph

Obstructed labor is one of the leading causes of maternal deaths worldwide [4], [14] and results from a disproportion between the fetal presentation and the mother's pelvis. The most recent statistics from the World Health Organization (WHO) show that 42,000 of all maternal deaths each year are caused by obstructed labor [4], [14]; however, this figure is likely underreported as obstructed labor most often leads to other conditions such as post-partum hemorrhage and sepsis, which are subsequently recorded as the proximate cause of death [14]. Obstructed labor is rarely a cause of maternal death in the developed world, where obstetric procedures (e.g., cesarean sections) and well-staffed and equipped facilities are the norm. Obstructed labor is also a major cause of maternal morbidities such as obstetric fistula, an isolating and painful medical condition where the tissue between the rectum or bladder and the vagina is worn away. Between 50,000 and 100,000 women are affected by fistula every year [15]. Without surgical repair, fistula can result in severe pain, infertility, fetid odors, and urinary infections, which can contribute to painful social isolation and abandonment by families and communities [4].

While many specific countries have adopted the partograph in clinical practice, global adoption began in 1987 during the Safe Motherhood conference in Nairobi, Kenya when the

WHO promoted the partograph as an essential part of maternal health improvement strategies worldwide. The WHO conducted the first large-scale partograph outcome study in 1994 with 35,484 women in Southeast Asia [3]. The results of this study showed that comprehensive partograph training for nurses, and subsequent use of the partograph in labor and delivery clinics reduced prolonged labor cases, labors needing augmentation, emergency cesarean sections, and stillbirths [3]. The 1994 WHO study underscores the significant impact of careful labor monitoring on maternal health outcomes in the developing world, and highlights the partograph as an inexpensive one-page form that significantly enhances birth attendants' ability to give patients the care they need.

1.3 Barriers to Partograph Use

Several recent studies in Kenya have reported a significant gap between partograph knowledge and practice. One study from the University of Nairobi showed that while 88.2% of the 1057 evaluated patient records contained a partograph, only 23.8% of the forms had been used correctly [8]. In a 1999 study of partograph use in Nigeria, researchers found that 94% of doctors thought the partograph was useful, although only 25% used it on a routine basis. In addition, only 35% of participants in that study could correctly explain the purpose of using the partograph [16]. These results are consistent with other partograph studies conducted in developing countries where lack of training and continuing education, exacerbated by limited resources, represent serious barriers to effective partograph use [6], [7], [17].

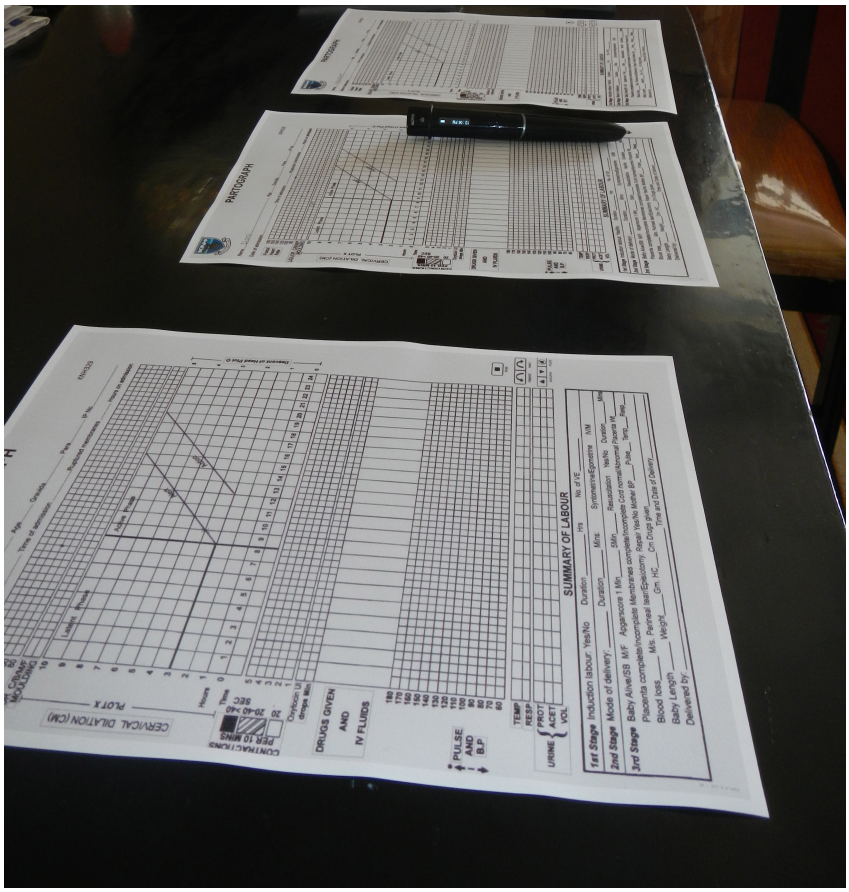


Figure 1: A photograph of the PartoPen and three interactive paper partographs.

The PartoPen provides a low-cost, intuitive solution to many of the barriers to partograph use in the developing world (see Figure 1). The PartoPen uses digital pen technology, which is unique in that it enhances, rather than replaces, the paper partograph system already in use. The PartoPen project addresses training and point-of-care issues without introducing significant training or financial costs. Further, even in the event of complete PartoPen failure (since a non-functional PartoPen is still a pen) practitioners are able to use the existing labor monitoring system exactly how they used it before the PartoPen was introduced – an essential feature for technological solutions deployed for "mission critical" systems like healthcare delivery.

1.4 Contributions of this Dissertation

The contributions of this dissertation work include:

1) A novel digital pen-based hardware and software system that helps address the issues of poor partograph completion and accuracy in developing countries, and that integrates available digital pen technology with existing paper-based labor monitoring tools [18];

2) An improved rubric for completed partograph evaluation that emphasizes elements of the partograph that are clinically relevant [19];

3) A multi-phase analysis of the qualitative and quantitative benefits of PartoPen use in maternity clinics and nursing classrooms in urban Kenya [19]-[22];

4) A set of recommendations that provide practical guidance for improving labor monitoring in developing countries [23]; and

5) An improved understanding of the relationship between partograph completion and clinical outcomes.

1.5 Research Questions

The research described in this dissertation describes the design, implementation and evaluation of technology designed to improve the accurate completion of the paper partograph form, which has been previously linked to reduced numbers of pregnancy-related maternal and child mortalities. The PartoPen is designed to reinforce birth attendant training on how and when to complete a partograph form, and to assist in decision support when labor complications are present. To evaluate the potential impact of PartoPen use during training and practice, two descriptive and two experimental studies were conducted. The research questions intended to be addressed by these studies include:

1) To what extent are nurses and nursing students willing and able to use the PartoPen system during their work in classrooms and clinics, respectively?

2) How do nurses' perceptions related to partograph use align with current partograph evaluation methods?
3) To what extent does the PartoPen improve partograph completion and accuracy among nursing students and nurse-midwives in Kenya?
4) Is the extant understanding of the relationship between partograph completion and clinical outcome supported by current practice?

These research questions were explored in four PartoPen studies that took place between March 2012 and June 2013. The next section provides an outline of this dissertation, which includes an overview of the PartoPen studies, and a discussion of the results.

1.6 Dissertation Outline

The contributions of this dissertation are advanced over the course of several chapters. Chapter 2 highlights the most relevant prior work in the fields of international development and global maternal health; information and communication technologies for health; technologies that integrate paper-and-pen-based approaches; digital pen systems; and partograph development, implementation, and evaluation. Chapter 2 thus provides the foundation on which the PartoPen project has been built, and illustrates both the enormity of global health issues and the technologies that have been developed to address them. The association between skilled birth attendants, labor monitoring, and positive maternal and child outcomes is outlined in Chapter 2, as are the barriers associated with the availability of skilled birth attendants and the delivery of quality labor monitoring services. The goal of Chapter 2 is to highlight the gaps that exist between quality healthcare in developing regions, and the technological solutions that have been designed to address those gaps.

Chapter 3 focuses on the technological implementation of the PartoPen system, and describes in detail the underlying hardware and software. In addition, Chapter 3 discusses several software tools that were developed to support data collection and survey analysis.

Chapter 4 describes in detail the four studies that evaluated the PartoPen system in urban Kenya. The first study, a user evaluation, was conducted in March 2012. The second two studies comprise the bulk of the research described here. Those studies were conducted in June-August 2012 at Kenyatta National Hospital and at the University of Nairobi School of Nursing Sciences. Upon the completion of the 2012 studies, KNH nurses and records staff sustained an ongoing deployment of 20 PartoPens for over nine months. Section 4.4 of Chapter 4 describes a follow-up visit conducted in June 2013, approximately nine months after the completion of the 2012 studies. This follow-up visit focused on gaining a deeper understanding of how nurses perceive 'complete' and 'useful' partographs, which provided critical input for evaluating the partograph grading rubric used in the initial PartoPen studies. The June 2013 study also provided longitudinal data regarding the impact of the PartoPen project at Kenyatta National Hospital. Chapter 4 concludes with a discussion of the results of the four PartoPen studies in aggregate.

Chapter 5 examines the PartoPen study results with an eye toward putting forth a set of best practices at the intersection of technology and healthcare, and critically examines several aspects of the PartoPen project that were considered unsuccessful.

Chapter 6 highlights areas of potential future work using PartoPen technology that would address other pressing issues identified by hospital staff and study participants. The account of a 2013 Maternal and Child Health Technical Working Group meeting in Kenya in this chapter provides a broader perspective of the issues facing maternal and child health, and places the conclusions of the PartoPen work in context with other efforts in this space. The dissertation

concludes with a summary of the primary contributions, the work performed, and how follow-on researchers might best use the results of this work.

2. RELATED WORK

This dissertation builds upon a rich body of prior work in five principal areas: international development and global maternal health; information and communication technologies for health; technologies that integrate paper-and-pen-based approaches; digital pen systems; and partograph development, implementation, and evaluation. This chapter summarizes the most relevant of this prior work that comprises the foundation of the PartoPen research project.

2.1 International Development and Global Maternal Health

This section focuses on the evolution of the United Nations Millennium Development Goals (MDGs), and how gender and maternal health, specifically in Kenya, have been affected by the MDGs. The MDGs are a globally recognized set of goals and specific targets for eradicating global poverty, and have motivated many of the development initiatives focusing on gender-inclusion and empowerment, and improving maternal health.

2.1.1 Evolution of the MDGs

In 2000, Kofi Annan, secretary general of the United Nations (UN), presented the Millennium Declaration at the largest gathering of world leaders in history, known as the Millennium Assembly. The Declaration surveyed the most pressing global issues, ranging from health and gender to poverty and education to global partnerships, and outlined eight global goals, 18 targets, and 48 technical indicators. These goals became known as the Millennium Development Goals (MDGs) (see Table 1). The comprehensive, normative nature of the goals and the systematic plan for implementing, financing, and monitoring them [24] were a significant departure from previous similar attempts to eradicate global poverty, and improve global health and well-being. At the time of their debut, the momentum of the economic boom

of 2000 and the rapid pace of technological advancement spurred the sense that these goals would be achieved in the spirit of 'global interconnectedness' [25].

The MDGs have been a source of controversy among development scholars, with scholars such as Jeffrey Sachs and William Easterly occupying different poles of the spectrum. Jeffrey Sachs generally describes the MDGs as a blueprint for the eradication of poverty worldwide [25], while Easterly views the MDGs as "The setting of utopian goals [that] means that aid workers will focus efforts on infeasible tasks, instead of the feasible tasks that will do some good" [26]. Despite these varying points of view, the MDGs have inspired global hope, and have caused an explosion of global awareness of issues in health, education, poverty, environment, and gender.

2.1.2 Evolution of Gender Inclusion in Development

The MDGs were the outcome of a concerted attempt to galvanize the development industry behind the most critical development concerns worldwide, as identified by the United Nations and a roster of high-level advisors. Prior to the MDGs, the World Development Report (WDR) and the Human Development Report (HDR) provided an annual snapshot of global development based on a large set of indicators. These reports were the first institutionalized effort to make a distinction between improving economic growth and improving lives; however, these publications did not set a particular development agenda [24]. The reports were also characterized by the emergence of the 'Capabilities Approach' to development [27]. This approach, conceptualized by Amartya Sen, broadened the narrowly economically-grounded definitions of development that had fueled the unsuccessful structural adjustment policies of the 1980s and 1990s [28]. Sen, and HDR author ul Haq, pressed for the inclusion of indicators of equity and freedom in the report; however, the first HDR did not include the majority of Sen and

ul Haq's proposed gender-focused indicators. Global development metrics are still largely focused on economic indicators, but the push for socially-focused indicators by proponents like Sen and ul Haq has supplemented global development reports with information on gender equity [29] and human development characterized by indicators such as education and healthcare access [30].

The UN has a long history of supporting gender equity initiatives as a development strategy. While there were only four women among the 160 signatories to the initial UN charter in 1945, the UN advocated for universal women's suffrage early in its history in 1946. At this time, only 30 of the 51 member states allowed women to vote. (Additionally, USAID, the US aid bilateral organization, has also focused on gender and development. In 1973, the US Congress passed the Percy Amendment, which required USAID development projects to include gender specifically in the implementation and evaluation [31]). In 1975 the UN organized a conference in Mexico City to initiate International Women's Year [32]. The tremendous energy and response to this conference spurred the UN Decade for Women (1976-1985) as well as World Conferences on Women every five years.

During the Decade for Women, the UN Convention on the Elimination of all forms of Discrimination Against Women (CEDAW)[1] was adopted, which was fundamental in drawing attention to rural women, women's health (especially reproductive rights), and the treatment of customs and cultural practices [33]. The Fourth World Conference on Women, held in Beijing in 1995, was the first of these conferences to include technology in the larger discussion of women's empowerment, discussing the Internet as an "activist venue" [33].

[1] As of 2011, 187 countries had ratified the CEDAW treaty, representing most of the developing world. The United States has not yet ratified CEDAW.

The UN member states, however, are not always united around gender issues. In 1996, the Organization for Economic Cooperation and Development (OECD) Development Assistance Committee (DAC), a sub-group of 'developed' and industrialized nations, formed the International Development Goals (IDGs). These goals were considered to be the first draft of the MDGs. The IDGs explicitly stated maternal and child health, *and* reproductive health access as development targets. In subsequent iterations of the IDGs, reproductive health was removed as an explicit goal because of religious and cultural conservatism present in several member nations, most notably the US [24], [34]. A UN consensus on the MDGs could only be obtained by removing reproductive health as an explicit goal.

2.1.2.1 Gender Theory in Development

During the various decades and conferences devoted to gender and development, competing and complimentary theories of gender and development have followed different trajectories and come in and out of favor. Of these, the Women in Development (WID), Gender and Development (GAD), Women and Development (WAD), and "Mainstreaming" are the most well-known.

The UN Decade for Women witnessed the evolution of the Women in Development (WID) approach to gender inclusion and recognition in development practices, which underscores how ignoring women's contributions is detrimental to development efforts. Development theories that use families or communities as the unit for evaluating development projects do not necessarily capture the uneven distribution of development occurring within families and communities due to gender discrimination [35]. Women significantly contribute to the economic and social capital within a family and a community, but are often overlooked by development projects with a community-level focus [35], [36]. The development project suffers

because it is not addressing the needs and existing resources of the entire community, and likely has little significant or sustainable impact, and the community suffers because a valuable contributing portion of its population is not receiving the development aid they need.

Ester Boserup brought the issue and concern for gender in development to the attention of an international audience in 1970 in her book, *Women's role in economic development* [36]. Boserup, generally associated with the WID movement, discusses the important role women play in promoting economic growth in developing countries, particularly in African countries. The Gender and Development (GAD) approach, which also took shape in the mid 1970s, focused on the underlying reasons for gender discrimination and took a more holistic approach to addressing gender inequality than proponents of WID [31]. Women and Development (WAD) contrasts both WID and GAD, which were primarily focused on the equality of white women in developed countries, by focusing on the unique factors of women in developing countries that contribute to inequality, including poverty and the effects of colonialism [37]. Finally, mainstreaming is an approach to development that focuses on balancing the considerations given to both women and men when designing, implementing and evaluating development projects [38]. Mainstreaming does not restrict its focus to any one population of women, and does not focus on the underlying issues causing gender inequality as in GAD. Mainstreaming is concerned with making sure gender is considered in all aspects of a development intervention, and thus is "mainstreamed" across the project.

2.1.3 Global Maternal Health and the Evolution of MDG 5

MDG 5 – reducing maternal mortality – has been a primary focus of the World Health Organization (WHO), a UN sub-organization founded in 1948 as the UN's designated agency in health. The WHO emerged as the amalgamation of the International Sanitary Bureau (1902),

which later became the Pan American Health Organization and the Office of Public Hygiene (1908). The WHO's role in global health policy is primarily to facilitate discussions among representatives of member states, and to document policy decisions resulting from these discussions. Although policies are voted on by members, the WHO is not tasked with enforcing the policy implementation at the national or regional level. Member state representatives, who often include ministers of health and ministries of health officials, are responsible for implementing health policies and initiatives at the state level [39]. The WHO was one of the key players in drawing attention to maternal mortality almost two decades before the launch of the MDGs. In 1987, the WHO announced the Safe Motherhood Initiative, which focused on reducing maternal and infant mortality in developing countries. Maternal mortality is defined as the death of a woman during pregnancy, childbirth, or in the 42 days after delivery [40]. In the 1987 "Safe Motherhood Call to Action," Halfdan Mahler, then Director-General of the WHO, highlighted the "neglected tragedy" of maternal mortality, and the effects of discrimination and poverty on the alarming rates of maternal death worldwide.

2.1.3.1 MDG 5 & Maternal Health in Kenya

The Safe Motherhood Initiative conference, held in Nairobi, Kenya in 1987 not only contributed to the momentum of the Decade for Women, but also published the first set of global data on maternal mortality rates for ten countries in Africa, Asia, and the Americas. "It has enabled us to correct the false impression which emerged from under-registration and thus to see, for the first time, the problem as it really is" [41]. One critical result of the conference was the adoption of the partograph as an integral part of the WHO strategy for preventing and reducing maternal mortality. The Safe Motherhood Conference demonstrated the link between maternal

mortality and gender equality. Health initiatives up to that point had largely ignored this link, and the conference helped to highlight the adverse consequences of doing so [40].

The WHO has actively pursued maternal health initiatives by launching training programs, supporting rigorous research on maternal health outcomes in developing countries, and publishing a comprehensive manual on preventing maternal deaths [42]. This manual, released in 1989, summarizes both the direct and indirect causes of maternal death, and looks at the roles of family planning and health services on improving maternal health worldwide [42]. The research reviewed in the WHO manual also highlights obstructed labor and its direct consequences as the most important causes of maternal death in Africa [42].

In 2000, the same year that the MDGs were declared, a review of the Safe Motherhood project in Kenya was published in the Reproductive Health Matters (RHM) journal [43]. The review discusses the socio-economic position of women in Kenya in the year 2000 and its direct impact on the Safe Motherhood project. The review reported that by the age of 15, 13% of women were married; by the age of 18, 34% of women had begun childbearing; and overall, 27% of women had no formal education. Women's limited knowledge of and access to healthcare services, lack of decision-making power in areas such as family planning and reproductive health, exposure to violence, and intense physical workloads regardless of pregnancy status were all significant contributors to the high rates of maternal mortality in Kenya, and in much of Sub-Saharan Africa. The review went on to cite important areas for improvement, including increased use of manual vacuum aspiration for the management of incomplete abortion, providing continuing education for midwives in the use of the partograph, and training traditional birth attendants [44]. In the early 1990s, in large part because of the increased attention to maternal health spurred by the Safe Motherhood Initiative, the National

Strategy for Reproductive Health Care was formed in Kenya to focus on a gender-sensitive approach to development [44].

In a 2001 study, the African Population and Health Research Center examined the factors associated with maternal mortality in Kenyan hospitals using multilevel logistic regression [45]. Researchers identified the factors most strongly correlated with maternal mortality rates to be maternal age, antenatal care, education level, and choice of hospital. The primary causes of maternal death were found to be anemia, post-partum hemorrhage (PPH), sepsis, malaria, delay, and eclampsia. The authors note that some of these statistics are confounded, however, due to the misreporting of the primary cause of death. "Delay," for example, was often cited as the primary cause, when obstructed labor had occurred due to the delay [45]. A 2010 WHO report showed that obstructed labor accounts for 8% of maternal deaths worldwide, but is often underreported or misreported as PPH or 'delay' [1]. Obstructed labor is defined as failure of descent of the fetus in the birth canal for mechanical reasons, in spite of healthy uterine contractions [44]. Obstructed labor is preventable by having skilled attendants at birth, appropriate monitoring during active labor, and accessible facilities capable of providing emergency obstetric care if needed [1]. However, in developing countries, these services and facilities are often unavailable due to transportation challenges, understaffing, and a lack of supplies [1], [2], [46].

The 2010 UN report on the progress of MDG 5 showed significant progress in many areas, but Sub-Saharan Africa continues to have one of the highest maternal mortality rates in the world. Sub-Saharan Africa has also experienced the slowest rate of decline in maternal mortality rates of any region in the world. 87% of maternal deaths worldwide occur in Sub-Saharan Africa and Southern Asia. The vast majority of maternal deaths are preventable, and the presence of a trained health-care worker during delivery "is crucial in reducing maternal deaths" [14]. Midwife

training and the presence of skilled birth attendants during labor have been the primary contributors to lower maternal mortality rates in countries that are "on track" to reach MDG 5, including Jamaica, Thailand, Malaysia, and Sri Lanka [14]. However, a systematic analysis of progress towards MDG 5 found that while worldwide maternal mortalities have decreased from 526,300 in 1980 to 342,900 in 2008, only 23 countries are currently on track to achieve the targeted 75% reduction in maternal mortality rate by 2015 [40]. Maternal morbidities, including vesicovaginal fistula – an isolating and debilitating disability caused by obstructed labor – also remain high with an estimated 10-20 million women worldwide developing pregnancy-related disabilities [47]. Like many maternal mortalities, maternal morbidities are generally preventable with skilled care and the availability of emergency obstetric procedures [14].

In 2010, the United Nations reported that MDG 5 had made the least progress out of all the goals [14]. This report spawned a wave of initiatives targeting maternal health, and has led to increased advocacy and education targeting the multitude of issues surrounding maternal mortalities in developing countries. The 2013 United Nations Maternal Health Report states that while worldwide maternal mortalities have decreased by 47% in the last two decades, Sub-Saharan Africa still has the highest maternal mortality ratio in the world [48]. This report also indicates that while the number of skilled birth attendants has increased worldwide, they are unevenly distributed, often concentrated in urban areas; and in 2011, 47 million babies were delivered without skilled care [48].

2.2 MDGs, ICTD, and Health

The MDGs have influenced the formation of international organizations, philanthropic branches of major companies, and academic disciplines [49]. Many of the initiatives and projects targeting the MDGs are using information and communication technologies (ICTs) as a platform

for development. The 2000 Millennium Declaration recognized the potential of technology to play a large role in the achievement of the MDGs, emphasizing partnerships to "ensure that the benefits of new technologies, especially information and communication technologies, ... are available to all" [50].

Part of the enthusiasm around the MDGs was created by the increasing speed of technological innovation. The discipline of Information and Communication Technologies for Development (ICTD) emerged out of the general consensus among global corporations, academics, and non-governmental organizations (NGOs) that technology had a critical role to play in promoting both economic growth and the participation and empowerment of individuals in developing countries ([49]. Some of the central tenets of ICTD include the recognition that socioeconomic and political contexts shape the potential of technology to support development; the acknowledgement that ICTD stakeholders have varying information and communication needs; the understanding that poor and marginalized populations have unique needs; and the knowledge that technologies must be appropriate for the context and conditions in the community in which they are implemented and deployed [49].

The field of ICTD is a diverse and interdisciplinary mix of academics and practitioners working toward the MDGs with ICT as the primary vehicle for promoting, implementing, and evaluating development work. ICT has been recognized as an enabler for impacting almost every sector associated with the MDGs [51]; however, technology alone is not enough to achieve progress in these sectors [52]. Table 1, taken from the 2003 World Telecommunication Development Report [53], highlights seven of the eight MDGs, their associated targets, and the potential role ICTs can play in achieving them. MDG 8 is "Develop a global partnership for development."

Goal/Target	**Role of ICTs**
1. Eradicate extreme poverty and hunger *Halve, between 1990 and 2015, the proportion of people whose income is less than one dollar a day. Halve, between 1990 and 2015, the proportion of people who suffer from hunger.*	Increase access to market information and reduce transaction costs for poor farmers and traders. Increase efficiency, competitiveness and market access of developing country firms. Enhance ability of developing countries to participate in global economy and to exploit comparative advantage in factor costs (particularly skilled labor).
2. Achieve universal primary education *Ensure that, by 2015, children everywhere, boys and girls alike, will be able to complete a full course of primary schooling*	Increase supply of trained teachers through ICT-enhanced and distance training of teachers and networks that link teachers to their colleagues. Improve the efficiency and effectiveness of education ministries and related bodies through strategic application of technologies and ICT-enabled skill development. Broaden availability of quality educational materials/resources through ICTs.
3. Promote gender equality and empower women	Deliver educational and literacy programs specifically targeted to poor girls and women using appropriate technologies. Influence public opinion on gender equality through information or communication programs using a range of ICTs.
4. Reduce child mortality 5. Improve maternal health 6. Combat HIV/AIDS, malaria, and other diseases *Reduce infant and child mortality rates by two-thirds between 1990 and 2015* *Reduce maternal mortality rates by three-quarters between 1990 and 2015* *Provide access to all who need reproductive health services by 2015*	Enhance delivery of basic and in-service training for health workers. Increase monitoring and information-sharing on disease and famine. Increase access of rural caregivers to specialist support and remote diagnosis. Increase access to reproductive health information, including information on AIDS prevention, through locally appropriate content in local languages.
7. Ensure environmental sustainability *Implement national strategies for sustainable development by 2005 so as to reverse the loss of environmental resources by 2015* *Halve, by 2015, the proportion of people without sustainable access to safe drinking water.* *Have achieved, by 2020, a significant improvement in the lives of at least 100 million slum dwellers.*	Remote sensing technologies and communications networks permit more effective monitoring, resource management, mitigation of environmental risks. Increase access to/awareness of sustainable development strategies, in areas such as agriculture, sanitation and water management, mining, etc. Greater transparency and monitoring of environmental abuses/enforcement of environmental regulations. Facilitate knowledge exchange and networking among policymakers, practitioners and advocacy groups.

Table 1: The Millennium Development Goals and associated targets, and a list of the role ICTs can play in achieving these goals [53].

2.2.1 Introduction to ICTs in Healthcare

Healthcare in both the developing and developed world has benefitted substantially from the use of ICTs in health-related applications. The ubiquitous use of paper records in healthcare worldwide has been a primary target for ICT initiatives that seek to digitize information to increase accessibility, training, monitoring and evaluation, and quality of care. The ubiquity and penetration of mobile devices in developing countries provides a potential platform for deploying development projects in rural or hard-to-access areas. The increasing use of mobile phones for healthcare projects is known as "mHealth." In the mid 2000s, mHealth supplanted the term "eHealth," which had been developed in the late 1990s to describe the use of desktop computers, electronic medical records, and the Internet in healthcare settings. mHealth, in contrast, encompasses all uses of mobile telecommunications for health care delivery, and emerged as a result of the growing use of mobile phones worldwide [54]. The International Telecommunications Union (ITU) reported in 2010 that mobile coverage (not necessarily devices) had reached 90% of the world's population, and 80% of populations living in rural areas [55]. In developing countries, the potential for low-cost ICTD projects to increase the reach and scalability of healthcare services, is especially important because of the unique resource-constraints that exist in these areas. The potential for ICTs in healthcare around the world has encouraged numerous global conferences, such as the mHealth summit which has grown from 800 participants in 2009 to over 4,500 in 2012, and interdisciplinary organizations, such as the United Nations' mHealth Alliance and GSMA (Groupe Speciale Mobile Association), which brings together governments, NGOs, and industry partners to promote the research and deployment of ICT mobile solutions for healthcare. The next section discusses relevant ICTD

projects focused on improving patient data collection and management, point-of-care support, and health promotion in the developing world.

2.2.2 Data Collection and Management

Some of the early ICTD work in the healthcare sector examined the use of smartphones to improve data collection and management for EMR systems and claim management, with the goal of streamlining healthcare processes with digital solutions that would improve upon or replace paper systems. One such project, ClaimMobile, developed a mobile phone application for provider reimbursement in a voucher-based health system in Uganda [56]. The needs assessment conducted for the Claim Mobile project found that health providers accepting pre-paid client vouchers were reimbursed several months after the client visit, and reimbursements were often for the incorrect amounts. The claim filing system was identified as the main source of reimbursement confusion and delay, and a smartphone application for data entry and management was proposed as a solution for streamlining this process. The smartphone application (Claim Mobile) was an *addition* to rather than a replacement for the existing paper-based claims form process, in that it was used as a check against the paper forms [56]. Introducing redundancy into the system by using both paper and mobile phone records had the drawback of doubling work for healthcare providers and their staff. The use of smartphones also exhibits limitations due to unreliable connectivity and power sources. In addition, the local partners involved with this project eventually changed the protocols they were using to deliver care using vouchers, and Claim Mobile was unable to scale and adapt to the changing system. The primary designer of Claim Mobile discusses in a 2012 paper how these limitations and challenges ultimately led to the "failing" of the technology and the discontinuation of the project [57].

In a 2008 paper on electronic medical record systems in rural Rwanda, researchers described a process for introducing technology into traditionally paper-based systems [58]. Anokwa et al. argued that understanding manual paper-based workflows is essential to the development and deployment of EMR systems, and they identified the areas in which an EMR system is superior to the existing paper system. These areas included generating patient IDs, entering lab data, and generating consult sheets. However, the authors also acknowledge that the use of smartphones or mobile devices introduces the costs of training and equipping providers with devices, and creates additional work by requiring manual data entry from paper forms into the EMR system. The authors conclude with a call for a closer examination of the appropriateness of technological interventions in paper-based workflows, as there are usability and cost affordances of paper-systems that have yet to be replaced by ICTs [58].

Treatment protocols are an example of hard-to-use paper-based systems because they are usually bound into bulky notebooks and binders, which are inaccessible for quick reference. In Tanzania, the IMCI protocol was designed to help healthcare providers diagnose and treat childhood illnesses. The e-IMCI project uses PDAs to replace the bulky paper protocols, and provides a form-based question workflow modeled on the IMCI protocol. The results of the e-IMCI study showed an increase in adherence to the IMCI protocols, and clinicians found the system faster than the paper alternative. There were some challenges with the ordering and presentation of the protocol questions, and some navigation issues as a result of the device and interface constraints. Clinicians participating in the e-IMCI study acknowledged the usefulness of integrating the PDA device with other protocols and systems such as training programs, label printers, and monthly reporting [59].

Open Data Kit (ODK) is another example of a digital mobile data collection tool. ODK is a set of mobile phone-based tools that collectively allow the development of custom information services for developing regions. ODK consists of three tools: Build, Collect, and Aggregate. ODK is compatible with the Android operating system, and allows users to create a custom data collection tool, collect data, and upload that data to a secure server [60]. ODK is an example of a extensible ICTD solution that can be implemented in a broad range of sectors for a broad range of services. ODK Clinic is a phone-based clinical decision support system (CDSS) that builds on the ODK platform to provide a health-specific application for patient data collection [61]. A 2012 study on ODK Clinic identified four "failure modes," that affected CDSS implementations in resource-limited settings: (1) unreliable movement of paper-based summaries, (2) incorrect data on computer-generated reminders, (3) untimely feedback, and (3) unreliable printing of patient summaries when patient influx is high. ODK Clinic completely replaced the existing paper-based system in the healthcare setting; however, the user interface of ODK Clinic was designed to model the paper-based system [61]. The usability study of ODK Clinic showed that it was considered easy and fast to use, but a lack of previous experience with smart phones and small phone screen size negatively affected usability. There were also concerns by doctors and physicians about distributing and securing phones that contained patient data [61]. ODK has hundreds of deployments worldwide, many of which focus on health data collection and improving community health worker (CHW) training and healthcare delivery.

2.2.3 Point-of-Care Support for Community Health Workers

The expense of training doctors and nurses, and the limited number of academic programs that offer such training in developing countries, have created a demand for a mobile, moderately trained workforce that can address common health issues throughout these countries.

Community Health Worker (CHW) programs in developing countries have attempted to fill that gap. CHWs are individuals from local communities who receive basic healthcare training, and then return to provide first line primary care in their communities. The information and communication needs of CHWs have been a primary area of ICTD's focus on healthcare. Three projects focusing on CHWs and community midwives are HealthLine, CommCare, and a portable ultrasound. All of these projects implement technology solutions designed to support community health workers at the point-of-care when interacting with patients.

The HealthLine system was created for CHWs in Pakistan [62]. An initial needs assessment in Pakistan revealed low-literacy rates among many CHWs, substantial knowledge gaps for several common diseases, and an inability to remember immunization schedules [62]. The HealthLine system utilized both cellular and landline phone networks to provide a speech-based information system for CHWs. In the initial pilot study of the HealthLine system, the majority of the participants found the system useful. The speech recognition system frequently experienced challenges with environmental noise, and the two-way dialogue structure of the audio prompts also proved challenging for both users and system developers. HealthLine researchers found that audio prompts needed to be recorded with different prosody (i.e., the rhythm, stress, and intonation of speech) in relation to the different context in which they would be used, and that a one-way lecture format (instead of a dialogue) was more successful in terms of usability and information transmission [62].

CommCare is another ICTD project that uses a phone-based system to strengthen community care by improving CHW effectiveness [63] CommCare is an open-source software platform that runs on a wide range of Java-enabled phones. One of the first deployments of CommCare was used to support CHWs providing care to HIV patients in Tanzania. CommCare

has also been used to strengthen CHW care for pregnant women in the Millennium Villages in Tanzania. CHWs were trained how to use the CommCare system to register patients and record follow-up visits. The initial results of the CommCare pilot showed that the built-in supervision (i.e., CHW supervisors could analyze CHW reports, registrations, and follow-ups with patients, and thus determine how well CHWs were performing) was the primary driver for increased patient registration and referral by CHWs. This result was emphasized by a significant drop in the number of CHW submissions following the conclusion of the research [63]. The CommCare study highlights the need for a rooted understanding of the needs of all stakeholders involved (e.g., CHWs *and* CHW supervisors.) Additionally, this research offers an example of how digitizing healthcare data, including metadata about CHW activity, is making the gaps in healthcare services more transparent and hopefully, easier to monitor and address.

Village midwives are a specialized subset of CHWs. Similarly to CHWs, village midwives typically receive minimal training and have limited supplies. A 2011 paper presented a portable ultrasound system designed for village midwives that took into account their limited training and resources. The system uses a low-cost touchscreen notebook and a USB ultrasound probe, which is also used in the MobiSante commercial mobile ultrasound application. The system integrates a continuing education module to supplement the midwives' limited training, and incorporates the option for networking and consulting with colleagues in other clinics [64]. A related needs assessment revealed that intermittent or nonexistent Internet would prohibit real-time collaboration and interpretation of ultrasounds images between clinics, which motivated the development of a robust help and asynchronous collaboration system. Future work is expected to evaluate this system with midwives in Uganda [65].

2.2.3 Health Promotion Tools for Midwives and Community Health Workers

The projects discussed in this section focus on supporting CHWs and community-based midwives through health education solutions and health promotion applications.

In India, Accredited Social Health Activists (ASHA) are appointed in each village to counsel and care for pregnant women, similar to the work of CHWs in Africa. Like CHWs, ASHAs often lack the training necessary to effectively manage the health and well-being of the pregnant women in their communities. To address this issue, a Microsoft Research project attempted to use a mobile phone messaging service to provide ASHAs with dialogue-based information to improve their interactions with clients. The results of this study showed that the mobile phone messaging service did increase ASHA involvement with clients, but there was debate regarding whether this was a result of the content, or because of the novelty of the messaging system itself. The ASHAs participating in this study also stressed the need for localizing the messages to the clients' native languages [66].

Midwives are the focus of one implementation of Mobile Technology for Community Health (MoTeCH), a project funded by the Grameen Foundation. MoTeCH uses mobile phones for both mothers and CHWs. Pregnant mothers receive relevant health information based on where they are in their pregnancy, and are encouraged to seek antenatal care from local facilities. Mothers are also provided with postnatal information about childcare after birth. CHWs use MoTeCH to track pregnant mothers in their community, as well as the information they have received [67]. At the 2011 FailFaire in Washington DC, a review of the MoTeCH project found that this system was not well suited for nurses in Northern Ghana, noting that nurses did not want to, or did not know how to enter data into the phones, and that the system added to their workload. The nurses using MoTeCH have since returned to a paper system supplemented by

mobile phone data collection tools. A more in-depth assessment of conditions on the ground, and a participatory action approach that involved the end-user in all stages of design, implementation, and evaluation were cited as key ways in which the MoTeCH project could have improved adoption and use by Ghanaian midwives [67].

A number of commercial applications also exist to educate communities about health practices, and to support public health initiatives. Text4Baby, for example, is a commercial application supported by Johnson & Johnson, that messages new mothers three times a week (until their baby is one year old) with content specific to where the woman is in her pregnancy [68]. FrontlineSMS is another text-based application that is free and open-source, and has been used in a variety of applications from education to health to environmental issues. FrontlineSMS allows users to send text messages to large groups or individuals, stores the text message data on a central computer, and does not require an internet connection because all data transfer is done via SMS [69].

2.2.4 Gender, mHealth, and ICTD

A literature review published in the Journal of Maternal and Child Health in 2010 examined several mHealth projects for maternal and newborn health [54]. The primary contribution of this review is the emphasis on the inclusion of local women in the design and implementation of mHealth projects. The authors examine the barriers facing successful operationalization of mHealth interventions, which include financial issues, policy frameworks, and socio-cultural context, particularly the exclusion of women in the design and implementation processes. mHealth has been an effective tool for empowering pregnant women and healthcare providers by expediting emergency obstetric referrals, bolstering preventive services, and enabling collaboration. The ongoing participation of local women in the design and

implementation of mHealth solutions has been a key factor in the success of these initiatives, because it has supported and driven ongoing adoption and use of the solutions [54].

Research on gender and ICT has illustrated that women have distinct information needs from men. Women face significant barriers to ICT access and use due to literacy, cost, work, and perceived relevance issues [70]. A number of other socio-economic barriers to female use of ICTs have been identified including various cultural attitudes that discriminate against women's access to ICTs. Women are less likely than men to own communication devices, women often experience income and literacy disparities that keep them from using public ICT facilities (which may also be located in places that women are uncomfortable visiting), and women have domestic responsibilities that keep them at home [70].

These and other gender-specific issues have become more visible in large part because of the growing research around ICTs. In a 2011 study of mobile phone use by midwives in Indonesia, the authors note that gender inequalities often remain masked until gradually revealed by ICT implementation [71]. This study found that while mobile phones improved professional efficiency and helped midwives gain the respect and confidence of their communities, gender-specific resistance to these improvements became more visible, e.g., power tensions with male family members [71]. The authors emphasized the potential unintended consequences of ICT deployments, and stressed the need for other researchers to recognize that technology is not gender-neutral [71].

Women's empowerment projects, such as Advancement through Interactive Radio (AIR) and Gender Research in Africa into ICTs for Empowerment (GRACE), have encouraged a dialogue with women in communities throughout all stages of development [72], [73]. The GRACE project, which comprises twenty-eight research teams in nineteen countries involved in

gender research in ICTs for women's empowerment, also emphasizes the range of experiences of women with ICTs, which are largely dependent on the socio-economic factors within their communities [72]. These projects have revealed local realities for women in rural communities that are not captured by the human development indices or ITU statistics, including unequal power relations within the home, and the important contributions of unpaid domestic work.

The growing focus on MDG 5 and global maternal health has promoted a closer examination of the relationship between women and the solutions designed to benefit them. The use of mobile phones has illustrated the benefits of using technologies that are already widely in use, but the ubiquity of mobile phones should not cause the complex socio-cultural contexts in which these devices are used to be overlooked. In addition, the constraints of many mobile phone systems have also been widely recognized in ICTD projects [49], [58], [61] especially when phone-based systems are intended to replace or supplement traditional and intuitive paper-systems. The following section focuses on ICTD projects that have attempted to find a middle ground between paper and digital systems in several sectors, including education, microfinance and healthcare.

2.3 Bridging the Gap Between Pen-and-Paper and Digital Devices

The concept of replacing paper systems with digital devices dates back to the early 1800s, when Samuel Morse first proposed transmitting data using electricity. The birth of the telegraph, the telephone and the phonograph in the late 1800s bolstered the idea that paper was a technology of the past [74]. Over a century later, paper is still an integral part of our everyday lives. The unique affordances of paper, including flexible document navigation, simple cross-referencing of multiple documents, annotation, and interwoven reading and writing [74], have not been sufficiently replicated or replaced by digital devices. The ongoing quest to replace

paper systems stems from the problems associated with paper-based organization, which include restrictive local use, physical space requirements, physical delivery, limited collaborative uses, arduous revising processes, replication limitations, and paper's static nature [74]. In addition, the cost of maintaining paper systems causes the lifetime costs of paper systems to outweigh the higher initial cost of digital systems.

In 2002, businesses in the United States spent $1 billion on designing and printing forms; $25-35 billion on filing, storing, and retrieving paper forms; and $65-85 billion on maintaining, updating, and distributing paper documents over the entire lifecycle of the document [74]. Taking the drawbacks of paper systems into account, it is not a stretch to see how new technologies continue to spur waves of excitement about "going paperless."

In developing countries, the high initial cost of digital systems is a significant barrier to their adoption. In addition, low technological literacy among the majority of the population in many developing countries is a looming hurdle to adopting digital systems [75]. Paper systems in these areas provide the affordances of being low-cost and ingrained into everyday use. Finding a balance between the affordances and persistence of paper, and the benefits of digital systems has been the primary motivation for several ICTD projects. Just as the telephone was thought to be a path to being paperless in the 1800s, mobile phones have been widely adopted as the ICTD platform of choice today. Mobile phones represent a low-cost platform that is available to over 90% of the population [55]. Several ICTD projects that incorporate the familiarity of paper systems with the increasingly ubiquitous mobile phone are described below in Section 2.3.1. The projects described here retain, to various degrees, rather than replace, existing paper systems. These projects also reveal some of the usability issues associated with using mobile phones as a

paper supplement; Section 2.3.2 highlights two alternative solutions for integrating paper and digital systems.

2.3.1 Mobile Phone Bridges

CAM was a mobile document-processing platform, developed in the mid 2000s, that uses Nokia camera phones to capture printed barcodes [76]. The developers of CAM – researchers at the University of Washington – recognized the usability difficulties associated with existing mobile phone interfaces, including data entry, screen size, and navigational paradigms (e.g., hierarchical menus, scrolling, etc.), and created a system that incorporated existing paper forms into the mobile data capture process. The goal of the CAM system was to combine paper, audio, numeric data entry, and asynchronous connectivity to provide the benefits of a digital system (efficiency of data entry and transmission, and digital record creation and storage) to low-literate populations using paper forms as a proxy. When the phone decoded the photo of the printed dataglyph, it triggered a set of conversational audio prompts, and asked the user to enter numerical data into the phone. The user, who may not be able to read the form, was asked via the audio prompts on the phone to enter the data into the phone that would normally be entered on the form. The CAM system illustrated the benefits of using an audio interface for low-literate populations, but faced scalability challenges due to the large number of paper forms that needed a customized code, corresponding audio, and non-numerical data entry. CAM also incurred multiple usability challenges, including user difficulty trying to capture the dataglyph using the smartphone camera [76]. Study participants had difficulty lining up the barcode in the camera viewfinder and capturing a clear image because of camera movement while taking the picture.

mScan, a 2011 University of Washington project used an Android smartphone camera and computer vision algorithms to decode and digitize multiple choice or “bubble” form data

(see Figure 2) [77]. mScan used a low-cost plastic tray to position the smartphone above the paper document. This reduced the usability issues observed with the CAM implementation by keeping the phone steady and focused during image capture. mScan researchers performed several experiments with dirty and crumpled/folded forms under varying lighting conditions. Detection accuracy of the mScan system under various suboptimal conditions varied between 81.54% and 99.95% [77]. Unlike CAM, the mScan system did not require any printed codes on the paper forms, and used a backend template-creation system that could be adapted to work with existing paper-forms. Initial mScan usability studies illustrated the need for quick template creation functionality, as well as manual data correction. mScan is currently limited to forms that use bubble and checkbox data entry, and by the general constraints associated with the use of smartphones for data collection and management (e.g., cost, connectivity and power). Future work on this project will focus on expanding the data input type from bubble forms and checkboxes to handwritten numbers. A crowd-sourcing component is also envisioned to assist in the categorization of non-machine readable data [77], [78].

These two projects illustrate that bridges between mobile phones and paper systems can be built, but integration of these systems presents both usability and contextual challenges. Additionally, several affordances of paper were not fully utilized in these systems, thus the paper was either a proxy for digital data collection or a redundant tool for recording data prior to digitization. A key goal of building a bridge between paper and digital systems should be to maximize the affordances of both types of platforms, including mobility, flexibility, and intuitiveness, and to not compromise the inherent functionality of either media.

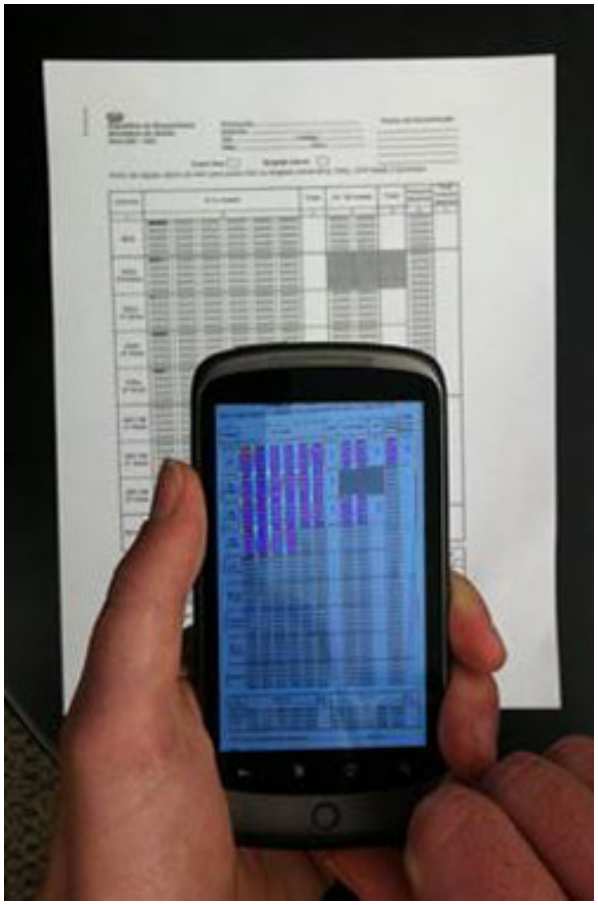


Figure 2: The mScan mobile phone application capturing form data from a paper document.

2.3.2 Tablet and Slate Bridges

Slate and tablet devices more closely bridge the physical gap between digital systems and paper and pen by retaining the gestures and movements of writing. Tablet PCs are a unique technological product that combines in a single device natural handwriting input capabilities with traditional keyboard and mouse data entry capabilities. The Classroom Presenter project [79] uses Tablet PCs to improve student engagement by providing real time feedback in classrooms using a shared whiteboard metaphor (see Figure 3). Classroom Presenter allows teachers to create interactive slide presentations where students can participate directly by annotating slides

on their individual Tablet PCs. While Classroom Presenter offers interactive distance learning, and provides a natural and intuitive mechanism for integrated note-taking [79], device cost and connectivity requirements are likely to hinder its widespread adoption in low-resource settings.

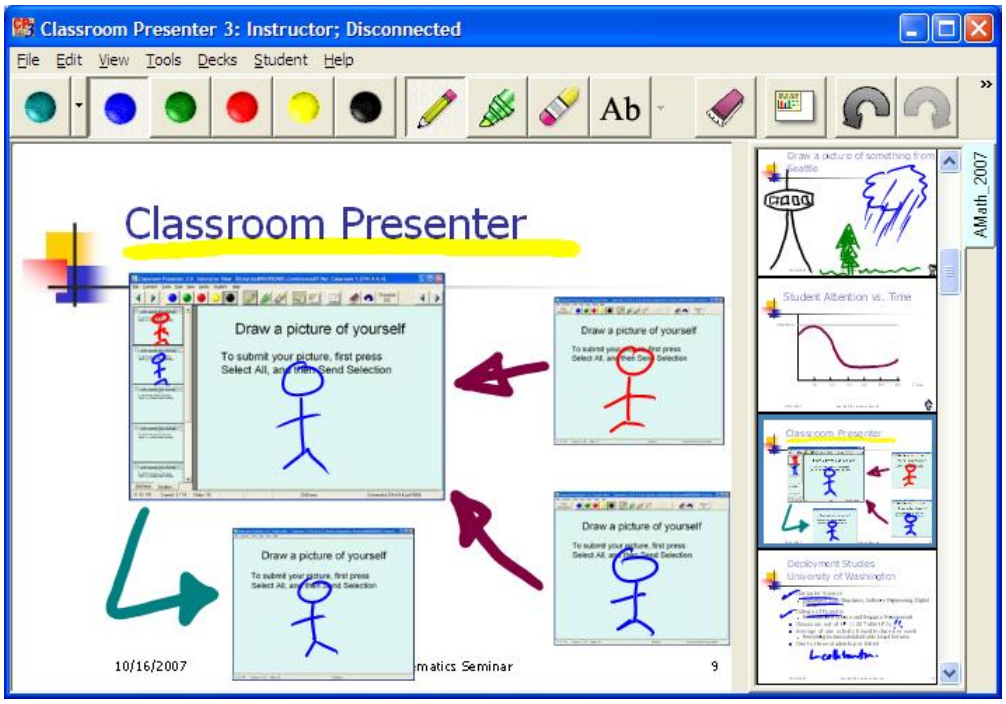


Figure 3: The Classroom Presenter interface. Classroom Presenter allows students to interact with teachers' slide presentations using tablet devices.

Microsoft Research created a digital slate device to improve record keeping for microfinance enterprises in India [80]. Project researchers identified six components of the current paper record keeping system that contributed to low data accuracy, completeness and efficiency, including recording errors, calculation errors, legibility errors, error resolution, form transportation delays, and extended meeting times due to manual data calculations. The resulting device resembles a traditional clipboard (see Figure 4). There is a flat surface for writing, and a small computer screen on the top where menus and entered data are displayed. Forms can be placed on the flat surface and filled out with the slate-specific pen. Data entered on the form

were recognized and displayed on the screen. A third-party handwriting recognition engine was incorporated into the slate device to support digit recognition during data entry. The system provided automatic calculations of fees and membership dues, instant reporting and updates, audio output for data verification, and a sequential data entry pipeline that enforced form completeness. The device supports audio, and speakers were attached to the digital slate for audio output during usability studies. The device itself was originally designed as a $100 note-taking PC for educational applications, but was not commercialized. The device had 512MB of memory and ran on rechargeable batteries. The slate-specific pen ran on a replaceable AAAA battery.

Use of this system improved record keeping accuracy and completeness, and reduced the time required for data calculation, error correction, and form processing. This was largely a result of local data processing on the device rather than remote, connectivity dependent data processing [80]. Users reported that the audio output feature was essential, especially for illiterate and low-literate users. Users also preferred the hybrid paper-digital system to a purely digital system because of the physical paper record that was produced. However, initial user evaluations of the digital slate device revealed that users experienced difficulties interpreting and understanding the data presented on the small screen display, and that navigation using scrollbars was unintuitive. Additionally, cost and device maintenance issues associated with the digital slate hindered the scalability and widespread deployment of the device. Researchers concluded that "it will be difficult to match the ease of use, simultaneous paper copy generation, and low cost of the paper-pen-digital slate solution using alternate devices such as a mobile phone or a netbook with an attached printer" [80].

Figure 4: The Digital Slate used in the microfinance application by Microsoft Research.

Worldreader, a non-profit created by Amazon executive David Risher, is experimenting with using the Kindle e-reader to provide digital books to children in developing countries. The low cost of publishing and distributing e-books makes e-readers appealing in resource-constrained areas. However, the Worldreader program is currently subsidizing the cost of the device and accessories, and the long-term viability of providing and maintaining e-reader devices is unknown.

The explosion of tablet devices that occurred after the first release of Apple's iPad has renewed the conversation about using these devices to bridge the gap between paper and digital systems. However, limitations including cost, content, and connectivity remain significant hurdles to the deployment of tablets in the developing world. The $35 Aakash tablet, developed

by DataWind in 2011, is being supplied to the Government of India in the hopes of providing a low-cost computing solution for education. The tablet has encountered many of the same criticisms as the One Laptop Per Child (OLPC) 2007 initiative, including lack of content or focused educational curriculum. OLPC released the XO Tablet in 2013 that runs different software than the original OLPC laptop, and provides more content and a more user- and child-friendly interface [81]. At this time, no data has been collected on the performance or adoption of the tablet.

Tablet and slate systems attempt to bridge the paper-digital gap by retaining the intuitive and easy-to-use input mechanisms (i.e., handwriting), whereas mobile phone applications often introduce extra work and usability issues [76], [77]. Both mobile phones and tablets/slates introduce a new component into the existing system – either an additional data collection step, or a new physical device. Digital pen technology, discussed below in Section 2.4 takes the concept of bridging the paper-digital divide one step further. Digital pens allow paper systems to be retained in their entirety, and no extra work is introduced because the paper and digital records are created simultaneously.

2.4 Digital Pen and Paper Systems

Over the past fifty years, a large body of work on pen-and-paper computing and pen-and-paper user interfaces (PPUIs) has been established. Much of this work falls into the categories of: digitizing paper content [77], [82]-[84], page identification and location tracking [85]-[88], capturing touch and gesture input [89]-[91], capturing pen input [92]-[94], digital output on paper [95]-[100], and augmented printed documents [101]-[106]. This section offers a brief history of digital pen technology, focusing primarily on projects that augment printed documents

and that capture pen input. The work discussed in this section will highlight key usability affordances of digital pen systems, particularly as they relate to healthcare-specific workflows.

2.4.1 History of the Digital Pen

Sketchpad, created at the Massachusetts Institute of Technology (MIT) in 1963, was the first system that made it possible for "a man and a computer to converse rapidly through the medium of line drawings" [84]. Sketchpad used a light pen to interact with a computer display, similar to a tablet and stylus system. The goals of Sketchpad were to improve the efficiency of generating computer diagrams, particularly of circuits and architectural structures, and to improve the accuracy and consistency of human generated drawings [84].

In 1968, Alan Kay of Xerox PARC proposed the Dynabook – the first conceptualization of modern laptop and tablet computers. The original concept for the Dynabook emerged from the need for a portable way to access military documentation, but Kay's primary motivation for the Dynabook was to give children access to digital media content [107]. The Dynabook was never actually constructed, but it inspired many laptop and tablet computers.

In 1991, GO Corporation created PenPoint OS – the first operating system designed specifically for graphics tablets. The GO system implemented a large set of recognizable handwriting gestures to control computer operations including insert, delete, and edit. The PenPoint OS established many of the foundations of pen-based user interfaces, and inspired other efforts to employ digital pen-like systems.

In 1991, Apple released the Newton computer, one of the first attempts to create what has come to be known as a "personal digital assistant" (PDA). Developers of the Newton computer sought to replace traditional mouse and keyboard input mechanisms by providing cursive handwriting recognition. Handwriting recognition on the Newton had limited success; the device

has been ridiculed in the popular media for its inaccurate and humorous word misrecognition [108].

DigitalDesk [89], in contrast to Sketchpad, sought to make the advantages of paper available in a digital format. The DigitalDesk was a physical desk with an overhead projector and camera that captured activity on the desk below. One application of the DigitalDesk was a calculator that let users point to a series of numbers on a paper document to perform calculations. The DigitalDesk responded to human touch or to input from a regular pen or pencil. Drawbacks of the DigitalDesk system included the limited mobility, and its extensive hardware requirements.

Digital pen technologies, like other computing technologies, have grown increasingly sophisticated over the last several decades. Technological advancement has made it possible to place computing power within the pen itself. Modern digital pens fall generally into two categories: pens that let users write anywhere on anything using wireless positioning technologies (Mobile Digital Scribe and Pegasus Tablet NoteTaker), and pens that require special paper to track pen movement [109]. Wireless positioning systems (WPS) – often embodied as an external device attached to sheet(s) of paper – allow users to write on any surface including large displays such as whiteboards and walls. WPS use triangulation of ultrasonic signals emitted by the digital point, which has a high enough spatial resolution to capture handwriting [110]. However, WPS does not differentiate between pages, and poses significant challenges in systems where multiple sheets of paper are used.

One implementation of pens that interact with special paper is the Paper++ project – a research project developed at King's College in London [93]. Paper++ uses conductive ink to print barcodes on paper documents. The digital pen measures the inductance of the ink and

decodes location information from the printed barcodes. The resolution of this technique does not support handwriting recognition, thus only interaction with large document areas is possible.

The current standard for printed paper with location-tracking dot patterns is the Anoto digital pen and paper [86]. Christer Fahraeus founded Anoto in Sweden in 1996. Fahraeus had the goal of "developing a high tech pen that could get the paperwork done more efficiently" [109].The Anoto digital pen contains an infrared camera capable of capturing an nearly-invisible pattern of dots printed on physical paper. The camera uses infrared technology to differentiate between the dot pattern and other printed content. To accomplish this, the dot pattern is printed with toner (black (K)) that absorbs infrared light, and the content is printed with other toner colors (cyan (C), magenta (M), and yellow (Y)). Anoto pens capture the dot pattern (of the small region beneath the pen's camera) at 75 images per second, with a spatial resolution of 850 dots-per-inch (dpi). This resolution is high enough to accurately capture handwriting and other pen strokes. The patented Anoto dot pattern, when printed directly on paper documents, makes documents slightly gray in color, but the effect is generally not problematic. The dots are arranged on an invisible grid that has lines in both the vertical and horizontal directions, which must be spaced 250 to 300 micrometers apart. Each dot is displaced from the gridline intersections in one of four directions (top, bottom, left, or right) a distance of 1/6 the distance between the gridlines – approximately 50 micrometers [111]. Each dot encodes two bits of location information (an X and a Y-coordinate) by translating its position marker (1-4) into its binary representation (see Figure 10 in Chapter 3). The location information stored in each 6x6 dot matrix encodes a unique position in the Anoto pattern space, and allows the digital pen to differentiate between areas on the page as well as between different pages. Anoto technology has been used in many digital pen systems, and became commercially available for the consumer

market in 2001 with the development of the Ericsson Chatpen CHA-30 and Logitech's io2 Digital Pen.

Low consumer demand for digital pen technology (likely due to price, limited functionality, and the limited number of feasible usage scenarios) led to the development of more focused products by digital pen companies. In 2006, LeapFrog targeted education with the Fly digital pen. The Fly pen offered educational games and interactive books for young consumers. In 2007, LeapFrog introduced the Fly Fusion, which improved the built-in MP3 player, added more memory, and introduced handwriting digitization [109]. Jim Marggraff, the CEO of LeapFrog, founded Livescribe in 2007, which sought to make digital pens more useful and appealing to a large consumer market.

Livescribe's most significant contribution to the evolution of digital pens was integrated audio recording [112]. Livescribe pens allow users to integrate written notes with recorded audio. The Livescribe Paper Replay application synchronizes recorded audio with written text so that users can tap the pen on a written word and hear the audio that was recorded when that word was written. Livescribe's development of integrated audio recording capabilities and improved handwriting recognition created several new opportunities for consumers and developers. Livescribe pens, in addition to providing audio recording and playback, included a processing unit capable of executing custom code, which allowed third-party developers to create custom applications for their smartpens. The Livescribe API builds upon the Java Platform Micro Edition (Java ME) and uses an Eclipse-based IDE with custom plug-ins for "penlet" and paper product development. The Livescribe SDK was available for free download until July 29th, 2012, when the company shifted resources and re-focused to developing networked and cloud-based applications [113].

Modern digital pens offer many of the benefits of mobile phones and personal computers including audio recording, network connectivity, ample storage and memory capacity, language translation, long-battery life, and the ability to create custom applications. The principle benefits of the digital pen are ease of use, familiar form and function, low cost (relative to tablets), seamless integration into existing paper-based systems, and the enhancement of paper-and-pen tools using audio, translation, and organic light-emitting diode (OLED) displays. In addition, some digital pens offer a unique social networking component that allows pen users to send emails, post to Facebook, or edit a Google Document directly from paper [114].

2.4.2 Digital Pen Applications

One of the early applications that used the Anoto technology was the Paper Augmented Digital Documents (PADD) system [101]. PADD explored the possibility of "cohabitation" between paper and digital documents facilitated by digital pens. The PADD system (see Figure 5) allowed users to edit and annotate paper documents with a digital pen, which would update the digital copy of the document. The revised digital document could then be printed, and would include the changes that had been made by the user on paper [101]. The creators of the PADD system extended its architecture with the PapierCraft project, which allowed users to manipulate digital content directly from paper using Anoto technology and a gesture recognition system. Using PapierCraft, the Anoto pen interprets specific markings on paper documents, and performs the associated command (following a hyperlink, copy and paste, stitching, etc.) The PapierCraft project differentiates between annotations and commands to increase the number of possible actions users can perform [91].

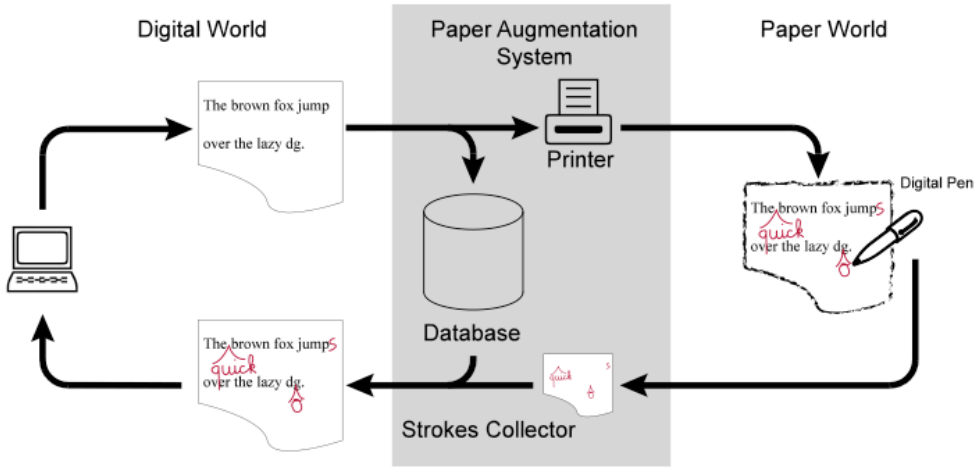


Figure 5: The Paper Augmented Digital Documents (PADD) architecture.

PADD did not interpret the marks made on the physical document, but rather, added them to the digital document as an additional layer. PaperProof, in contrast, interpreted marks made by the digital pen on a paper document and translated these markings into common OpenOffice editing functions such as insert, delete, highlight, and move. The goal of PaperProof was to provide a seamless editing platform that allowed users to edit on paper, and have their changes reflected on the digital document [102].

PaperPoint, developed by the same research team as PaperProof, introduced the concept of custom form production to enhance traditional PowerPoint slide presentations. PaperPoint used Anoto technology to allow users to control a slide presentation using a digital pen. Paper Point also allowed the creation of custom paper handouts of slide presentations. Using PaperPoint, a presenter did not have to stand near a computer or have a remote to control the slide presentation. Presenters could also tap on a particular paper slide to trigger that slide to be displayed [103].

Other applications using Anoto technology have focused on the context-specific needs of researchers [115], sketching and social networking [116], and improved accessibility for persons with disabilities [117].

Many of the applications discussed in this section use digital pens and paper only as an input mechanism for digital systems, such as a PC or tablet. In contrast, the PenLight and MouseLight [105], [106] projects used mobile projectors attached to the pen to create a standalone system that both captured digital pen input and projected digital data on the same piece of paper. The low brightness level of the projected image and other usability issues related to having the projector attached directly to the digital pen (in the case of PenLight) limited the adoption of these systems.

The rapid evolution of digital pen technology has spawned several applications that attempt to provide digital benefits to traditionally static paper systems [110]. The extensive use of paper in healthcare systems worldwide for medical records, doctors' notes, prescriptions, forms, and information brochures make hospital workflows an obvious area for digital pen applications, as discussed below.

2.4.3 Digital Pens in Healthcare

In 2003, a home-based palliative care system using Anoto digital pens was implemented at Linkoping University Hospital in Sweden [118]. This system allowed home-based patients to record their symptoms and medications using a digital pen and a pain-diary printed on dot pattern paper. These patient diaries were then transmitted to the hospital using GSM/GPRS cell phone networks, and stored in a central database. This system made it possible for patients at home to be remotely monitored by hospital staff, and provided a digital record of the information

recorded on paper. Hospital staff used the digital record to track patient conditions over time, and to quickly produce patient histories.

The deployment of new data collection technologies in a hospital or clinical setting often faces barriers including cost, wireless connections, device robustness, weight, size, battery life, screen size, input methods, and cultural acceptance by clinicians and patients [119]. Retaining the accepted existing system of paper-and-pen in hospitals has been praised as "the most-cost effective, efficient, and easy to use means of acquiring data" [120].

Yen and Gorman conducted a usability study in 2005 with 21 nurse volunteers from a local labor and delivery ward to determine the feasibility of implementing a digital pen and paper system in the ward [121]. One form, the "Admission Database" was chosen as the task for evaluating the digital pen system. The digital pen used in this study was the Logitech io2 digital pen, which relied on the Anoto dot pattern to interact with paper documents. Each nurse received his/her own pen and was asked to complete a questionnaire, and participate in an interview. Researcher observations of the task completion portion of the study revealed that there was a significant amount of initial excitement about using the digital pens, but after a few days, the nurses were using the digital pen to complete only the Admission Database form, and regular or more accessible pens for all other tasks. Pen preferences emerged after one week of use, and a significant preference for regular pens was identified, due to perceived ease of use (the digital pen was bulky), compatibility issues, and the low quality of character recognition. In addition, because the pens used in this study were designed for individual rather than clinical use, the nurses found the pen to be a distraction that detracted from patient care. During the study several significant behavior changes occurred including where and how nurses carried the digital pen (some of them created lanyards to wear them around their necks), and "quitting" regular pens by

forcing themselves to only carry the digital pen. Although there were several usability issues with system, the authors reported that nurses were generally positive about using the digital pens, and saw potential for their widespread use after the usability issues were addressed. One important contribution of this study was the recognition of the environmental changes caused by the digital pen intervention. Despite the integration of digital pen technology into existing paper-based systems, the installation of charging stations and procedural changes, such as pen-to-computer data upload, significantly changed clinical workflow. This result suggests that digital pen-based usability studies consider the system as whole, rather than focusing solely on the digital pen [121].

Digital pen technology has also been evaluated in acute care settings for capturing patients' vital sign data. In a 2006 study by Dykes et al., digital pens were used to create a bridge between the preferred paper-and-pen system and the electronic medical record (EMR) systems deployed at Brigham Women's Hospital and Massachusetts General Hospital [122]. This study improved upon earlier deployments by providing pen lanyards, increasing the availability of pens by installing docking stations at multiple locations throughout the wards, and conducting training sessions with the nursing staff on how to print documents and troubleshoot the system. Data recorded with the digital pen were classified into the following categories: accurate, data missing due to no value on paper form, data missing due to handwriting recognition, data missing because data was recorded outside of the box, data missing because data value was out of range, and inaccurate because of handwriting recognition. Using this categorization technique on 899 vital sign records, digital pen data was found to be 91.9% accurate. This study focused on digital pen usability, and thus did not compare the accuracy of the digital pen data to the accuracy of data collected with regular pens. The 8.1% error was primarily related to handwriting

misrecognition by the pen. The authors also found that the nursing staff used the digital pens during all shifts every day for the duration of the study, despite having access to non-digital pens. This finding suggests that the digital pens were an acceptable addition to the current system and did not disrupt the workflow or nurses' ability to provide quality care.

A qualitative and quantitative study conducted in 2007 by Estellat et al. evaluated the use of a digital pen system by 27 anesthetists in a clinical setting [123]. The study compared the use of a digital pen system with the manual data-entry system currently in use by variable type (tick boxes, numbers, letters, dates, etc.) Because this study used Anoto technology, the forms used for data collection were printed with the unique dot pattern, and specific areas on the form were programmed to correspond to specific fields in an online database. The database fields were automatically filled when the digital pen was docked. Study participants reported that having the data readily available was the main advantage of the system, while the main hindrance was the time-intensive internet data verification process. The primary findings from this study showed that the digital pen system was easy to use and intuitive, but that nurses would not always use them in front of patients [123].

The flow of information from paper systems to EMR systems was the focus of a 2009 study conducted by Tang and Carpendale [124]. Anoto technology was used to create personal note templates for nurses. The unique charting interface implemented in this study allowed nurses to create, save, and print their own customized forms before their shifts. Handwritten notes created on these personalized forms were digitized by docking the pen, and added to the "notes" section of a patient record. Nine nurses and three nursing students evaluated the system, and participated in six focus group discussions. While this study illustrated many strengths of the digital pen system, several important weaknesses were also identified, including concerns over

loss or theft of the digital pen, cost, and poor handwriting recognition for (non-standard) medical abbreviations and symbols [124].

One unique use of digital pens in the healthcare sector is the integration of handwritten notes and wall-mounted displays in emergency rooms. The TraumaPen [125] integrated with the current paper-based system of emergency patient intake, and added a digital display component that reduced the redundancy of verbal data transmission between health care practitioners. At the time of writing, the TraumaPen is being evaluated at several hospitals on the East Coast.

2.4.4 Summary

"The paperless office is a myth not because people fail to achieve their goals, but because they know too well that their goals cannot be achieved without paper."[74]

Digital pen technology has tried repeatedly to connect paper to the array of digital technology. As digital pens acquire more functionality, including audio, improved handwriting recognition, wireless connectivity, the number of use-case scenarios will increase. The field of healthcare in both developing and developed countries relies heavily on the use of paper for record keeping, notes, files, and prescriptions. The sensitive medical information exchanged in these environments, and the need for efficiency and accuracy, creates an environment that would benefit from digital solutions. Digital pen systems provide a technological solution that does not impose a significant training overhead for busy hospital staff, and offers digital advantages at a low cost without replacing the trusted and intuitive paper systems already in use. In developing countries in particular, healthcare clinics face a number of additional challenges including chronic understaffing, inadequate training of staff members, a lack of equipment and resources, and significant distance and transportation issues for patients. The use of paper in these settings is ubiquitous, and the general level of technological knowledge among hospital staff is low.

Digital pen technology has a great potential to impact the quality and consistency of paper systems in such settings. The next section highlights one such paper system.

2.5 The Partograph

The partograph is a paper form designed to assist birth attendants in monitoring maternal labor. The partograph, in contrast to free-form handwritten labor monitoring notes, provides a graphical representation of the labor over time. The graphical representation allows birth attendants to reference labor progress as a whole, and quickly make decisions about care procedures for that patient. The partograph, when completed correctly, is particularly useful for helping birth attendants detect labor complications such as obstructed labor.

Obstructed labor resulting from a disproportion between the fetal presentation and the mother's pelvis, is one of the leading causes of maternal deaths worldwide [14]. The most recent statistics from the WHO show that 8% (42,000) of annual maternal deaths are caused by obstructed labor [4], [126]. Obstructed labor is rarely a cause of maternal death in the developed world, where obstetric procedures (e.g., cesarean sections) and well-staffed and equipped facilities exist. In the developing world, however, deaths due to obstructed labor are often underreported because complications caused by obstructed labor, such as hemorrhage and sepsis, are often reported instead [4]. Obstructed labor is also a major cause of maternal morbidities such as obstetric fistula. Between 50,000 and 100,000 women are affected by fistula every year [15]. Without surgical repair, fistula can result in severe pain, infertility, fetid odors, and urinary infections, which all contribute to painful social isolation and abandonment by families and communities.

Early attempts to predict obstructed labor used indirect physical markers such as small shoe size or pelvis size to determine potential at-risk women; however, the predictive power of

these metrics was low [127]. Other attempts at predicting obstructed labor before birth, including ultrasound and x-ray pelvimetry, have also been shown to be ineffective at predicting obstructed labor [4]. Labor itself is currently the best predictor of obstructed labor [4]. Assessment of labor by careful monitoring, and skilled attendants at birth are currently the best methods of predicting and preventing obstructed labor and its resulting complications [4].

The partograph is designed to assist in labor monitoring, and improve the ability of birth attendants to predict and prevent obstructed labor. The partograph has a long history. Emanuel Friedman, an MD in the Department of Obstetrics and Gynecology at Columbia University, first established "normal" labor cervical dilation curves in 1954. By evaluating 100 primigravid (women pregnant with their first child) women, Friedman determined that the graphical representation of cervical dilation versus time for normal labors produced almost identical sigmoid S-curves with varying slopes. Additionally, Friedman identified four distinct phases of cervical dilation – the latent phase (< 3cm dilated), acceleration phase (1cm per hour increasing dilation), maximum slope (rapid dilation with variable timing), and the deceleration phase (slowing of cervical dilation while approaching 10cm). The result of this research known as the "Friedman curve," showed a graph of expected normal cervical dilation (plotted on the Y axis) over time (plotted on the X axis). The "cervicograph," a variation of the Friedman curve, provided a blank graph to be used for monitoring cervical dilation in real-time during labor. Friedman's discovery provided the basis for a graphical tool for monitoring individual labors and detecting pregnancy complications [9].

In 1965, R. H. Philpott, a professor of obstetrics and gynecology at the University of Rhodesia, proposed using the cervicograph with the specific goal of detecting abnormal labors. In 1971, Philpott created the partograph (Figure 6), which incorporated the cervicograph with

several other metrics for monitoring labor progression including descent of the fetal head and contraction patterns [10]. Philpott used Friedman's data on normal labor progression to add decision support to the cervicograph. He added two parallel lines to the cervicograph – the "Alert" and "Action" lines. These "Alert" and "Action" lines were designed to provide a guide for detecting deviations from normal labor progression. The "Alert" line is a modified representation of the mean cervicographic progress of the slowest 10% of normal primigravid patients. The "Action" line is drawn four hours to the right of the alert line, to allow time to transfer patients to a hospital or allow normal patients to deliver vaginally without active intervention. The other components of the partograph include graphical representations of fetal heart rate, amniotic fluid, molding, contractions, descent of the fetal head, blood pressure, pulse, temperature, urine production, and administered drugs. Initial studies of the partograph in use at the Harare Maternity Hospital in Salisbury, Rhodesia (now Zimbabwe), illustrated that these graphical records significantly improved the management of labor of the individual and the administration of the labor ward as a whole [10]. The partograph was more efficient than lengthy handwritten notes. It provided a pictorial display, which immediately alerted attendants to abnormal developments, and was suitable for small peripheral clinics where staff shortages necessitated a simple efficient method of recording. Philpott also illustrated the benefits of using a partograph to teach medical students and midwives how to recognize and manage normal and abnormal labors [10].

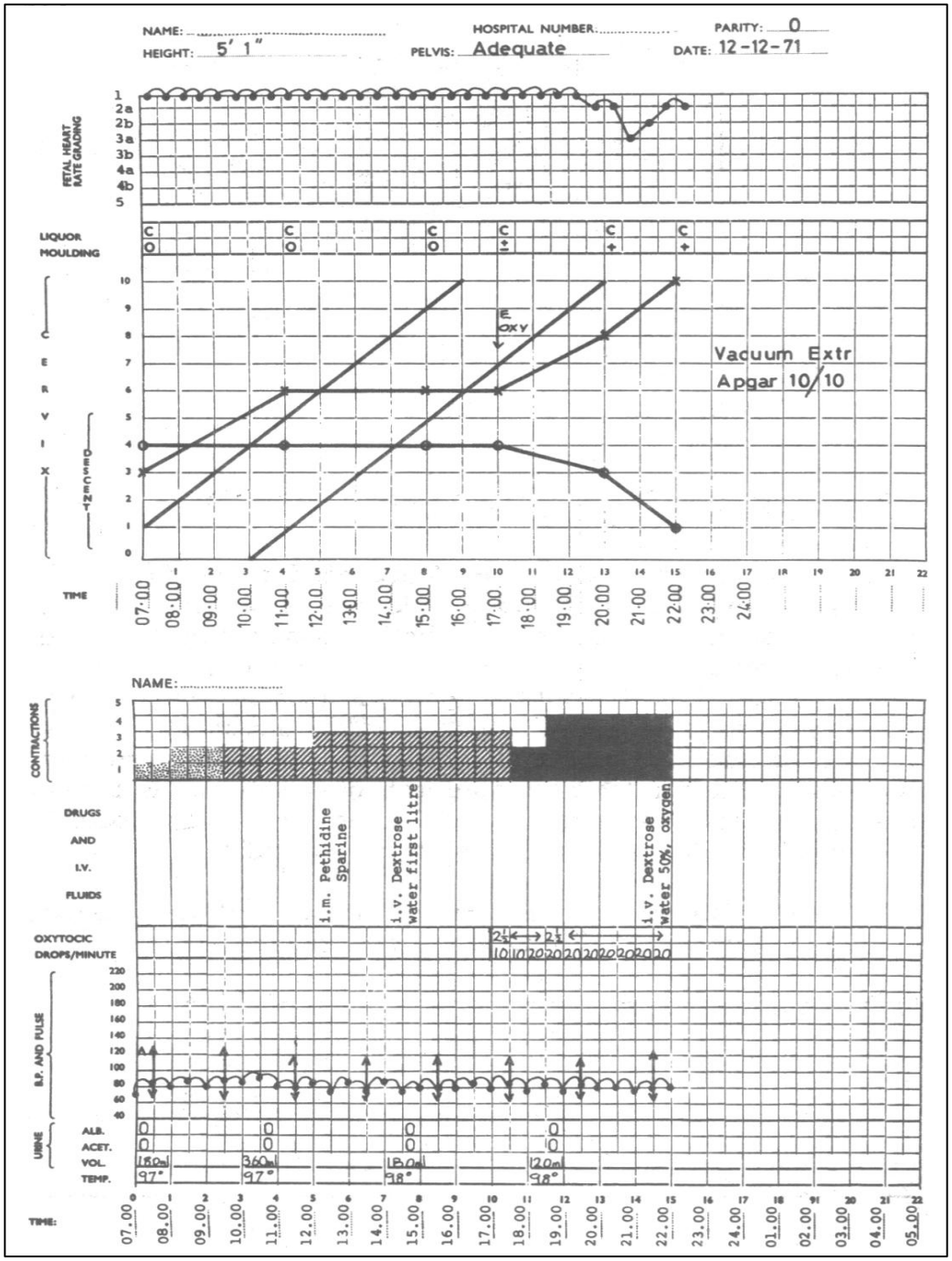


Figure 6: Philpott's original partograph (1971)

The partograph was introduced in England in 1973 [11]. English physicians made several revisions to Philpott's original partograph, including removing the Alert and Action lines because of perceived racial differences in labor progression times. Researchers later illustrated

similar cervical dilation curves for 4000 women from varying racial groups [11], and the Alert and Action lines were re-instated when the partograph was introduced to the United States and Ireland later in 1973 [128]. Despite early research illustrating that correct use of the partograph reduces prolonged labor, cesarean sections, labor augmentation, and stillbirths, there has been little documented partograph research on the partograph since the 1970s [128].

In 1987, the World Health Organization, as part of the Safe Motherhood Initiative, began promoting partograph use worldwide in an attempt to address the rising maternal and fetal mortality rates in many areas of the developing world [41], [128]. Due to the lack of current and reliable research on partograph use at the time, the WHO conducted a study on partograph impact in 1990 with 35,484 women from Southeast Asia; 13,803 women from Indonesia, 12,054 women from Malaysia, and 9,627 women from Thailand [3]. The partograph used in this study is shown in Figure 7. Eight hospitals participated in the 15-month study – four control hospitals and four test hospitals. Each control hospital was compared with one test hospital based upon similar demographic and economic data. During the first five months, all of the hospitals collected data about deliveries without using the partograph. During the second five-month period, the partograph was randomly introduced to one hospital in each hospital pair. For the last five months, all of the hospitals were trained and using the partograph regularly. The results of this study, published in 1994 [3], showed that correct partograph use significantly reduced the number of emergency cesarean sections, number of postpartum sepsis cases, prolonged labors, and stillbirths.

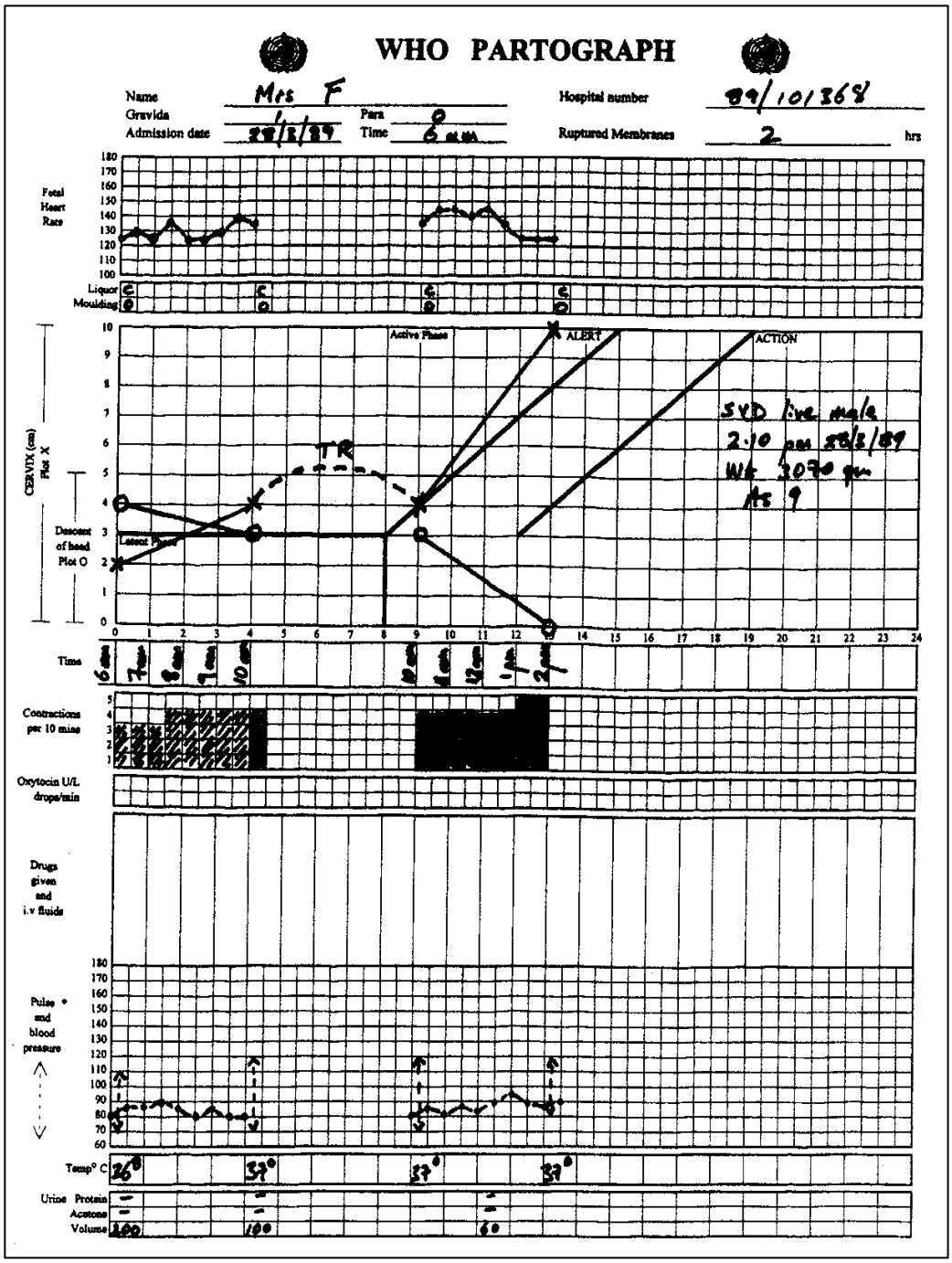


Figure 7: World Health Organization partograph used in 1990 Southeast Asia study.

Following this study, the WHO advocated universal use of the partograph for managing labor, and developed a series of protocols, guidelines, and manuals to assist with teaching and implementing the partograph worldwide [3], [128], [129]. The WHO also proposed four areas for

further research on operational partograph use, including assessing the effectiveness of health worker education programs on correct partograph application, determining the effect of the partograph on patient referrals, determining the effect of the partograph on the incidence of prolonged and augmented labors, and evaluating the effectiveness of the interventions resulting from partograph use [13].

2.5.1 Partograph Education and Training

Correct use of the partograph in developing countries is often limited by the training birth attendants have received [130]. Further, even when midwives and doctors are trained in the use of the partograph, correct usage of the partograph is often low [13], [16]. In a 1999 study of partograph use in Nigeria, researchers found that 94% of doctors considered the partograph to be useful, although only 25% used it on a routine basis, and only 35% of participants could correctly explain the purpose of using the partograph [16]. A 1993 study in Kenya showed that 50% of healthcare workers had low partograph knowledge, and partograph information was rarely used to make clinical decisions. In addition, 60% of participants could not correctly apply partograph data to actions in labor management situations [131].

In 2007, Fatusi et al. evaluated a Nigerian training program designed to improve partograph use. The training sessions utilized WHO manuals and facilitator guides, and participants were supervised for two weeks following the initial trainings. The trainings emphasized the use of the partograph for early detection of at-risk pregnancies, so that patients could be referred to appropriate facilities when needed [132]. Researchers found that primary health care workers with little or no formal education can be effectively trained to use the partograph [132].

A study conducted in 2007 in the Western Province of Kenya showed that the Safe Motherhood training program increased partograph use by 74%, with a corresponding improvement in record keeping and labor management [131]. However, one-time training did not show a long-term impact on partograph use. The potential for continuing education programs was not addressed. Several other studies have shown that it is necessary to provide ongoing education, supervision, and quality assurance measures in order to have a lasting impact on partograph completion and quality [13], [133], [134].

2.5.2 Partograph Impact on Patient Referral

Kenya has a pyramid-structured health care systems similar to that of the British National Health System (NHS). Primary care facilities are designed to deal with general health issues. In the case of childbirth, these facilities are usually equipped to handle uncomplicated labors. Secondary and tertiary care facilities are the next two levels of the pyramid structure. Tertiary care facilities provide complicated procedures and handle the most severe medical cases. Kenyatta National Hospital is considered a tertiary care facility, as it handles referral patients from numerous primary and secondary care facilities from all over the country. When pregnancy complications arise in primary care facilities, patient referral to a central hospital is often necessary so that the patient can receive necessary care. The partograph is designed to promote patient referral by detecting potential complications early in labor; however, the partograph can only be useful as a referral tool if referral is a viable option [13]. Transportation, cultural contexts, hospital expenses, and reluctance to believe partograph data all have been cited as causes of low referral rates [134].

In a 2012 study in Nairobi, Kenya, qualitative evidence suggested that primary-level health clinics fear that partograph data will be used to reprimand district level hospitals for

mismanaging patients. This tension between primary, secondary, and tertiary clinics results in an ineffective referral system, where patients are often transferred too late to receive effective care, leading to pregnancy-related disabilities or death [22]. In addition, partographs are often not transferred with patients to central facilities because of record management protocols at lower-level clinics [22]. Lower-level clinics often keep the paper records even when patients are referred so that funding (based on the number of documented patients a clinic receives) will continue to be provided.

2.5.3 Partograph Impact on Maternal Outcomes

The 1994 WHO partograph study in Southeast Asia has been criticized for the methodology that was employed, and for using the results, which were confined to tertiary hospitals, as the basis for recommending the partograph for worldwide use [135]. In the years following the 1994 WHO partograph study, researchers conducted a number of smaller studies in an attempt to determine the impact of partograph use on maternal and neonatal outcomes [13]. These studies revealed a strong correlation between geographical location and partograph impact. The Cochrane database review – a review of five randomized control trial partograph studies – illustrated the difference in the impact of the partograph on maternal outcomes between developing and developed countries. The studies conducted in developed countries exhibited no significant differences between partograph and no-partograph groups. In developing countries, however, partograph use resulted in a reduction in cesarean section rates and early intervention for delayed progress in labor [13], [136].

USAID conducted a comprehensive literature review in 2011, which examined the outcomes of partograph studies performed in both developing and developed countries [137]. The results of this review are summarized in the table below.

	Lowered/Improved	Neutral	Increased/ Worsened
Cesarean Rates	1) Pattinson et al. 2003 2) Fawole & Fadare, 2007	1) Lennox, Kwast, & Farely, 1998 2) Bosse, Massawe, & Jahn, 2002	None
Labor Augmentation	1) Javad, Bhutta, & Shoaib, 2007 2) WHO, 1994	None	1) Fawole & Fadare, 2007
Perinatal Outcome	1) Fahdhy & Chongsuvivatwong, 2005 2) Javed, Bhutta, & Shoaib, 2007 3) Bosse, Massawe, & Jahn, 2002 4) Lennox, Kwast, & Farely, 1998 5) Fawole & Fadare, 2007	1) WHO, 1994	None
Maternal Outcome	1) Fahdhy & Chongsuvivatwong, 2005 2) Javed, Bhutta, & Shoaib, 2007 (primigravidae only) 3) Bosse, Massawe, & Jahn, 2002 4) Fawole & Fadare, 2007	1) WHO 1994 (maternal death and postpartum hemorrhage) 2) Javed, Bhutta, & Shoaib, 2007 (multigravidae only)	None

Table 2: Summary of partograph studies and outcomes [137].

Taken as a whole, these results demonstrate that the partograph use positively impacts some aspects of maternal and neonatal outcomes in the developing world, but additional randomized controlled trials are needed to evaluate fully the effectiveness of the partograph in improving medical outcomes and improving overall care.

2.5.4 Barriers to Partograph Use

In addition to inadequate training programs several other identified barriers to partograph use in developing countries include supply issues, staffing shortages, and a lack of understanding or use of the partograph as a tool for action when necessary [137], [138]. A 2011 study of nursing students in Nairobi, Kenya discussed resource constraints, poor teaching, a disconnect between theory and practice in partograph training, retrospective partograph completion, and a lack of positive reinforcement for completing partograph forms post-training [8]. Another 2011 study in Kenya, conducted at nine health facilities, reported the main barriers to partograph use to be staffing shortages, and supply shortages of the tools required to take measurements needed

to complete the partograph (e.g., fetalscopes and blood pressure machines) [7]. The Cochrane review, mentioned previously, stated that while midwives often felt that the partograph was a useful tool, midwives in higher-resource settings criticized the partograph for disrupting clinical practice and reducing midwife autonomy [136]. This attitude is largely a result of the extensive training that midwives in high-resource settings are able to receive, and the wider availability of facilities for performing emergency obstetric procedures.

2.5.5 Partograph Solutions, Simplifications, and Alternatives

Figure 8: Four partograph tools. The round partograph, top left; the "paperless partograph", top right; the e-Partogram, lower left; and the WHO e-Learning tool, lower right.

Low-cost alternatives to the standard WHO partograph include simplified partographs [4], [139]-[142], and a partograph training program CD-ROM produced by the WHO (see Figure 8 for several examples of alternative partograph tools). The WHO has produced two simplified versions of the partograph form since the 1994 study. The first simplification, published in 2000, did not include the latent phase of labor on the cervicograph [139]. The second WHO simplification included color-coding for easier detection of abnormal labor progression [140]. These small changes to the original partograph simplify the form somewhat, but they do not directly address the barriers associated with inadequate training and continuing education. To this end, the WHO created the partograph eLearning tool, which is a CD-ROM tutorial designed to teach midwives and birth attendants how to plot and interpret data on the partograph.

The E-Partogram project, started by John's Hopkins University and the associated non-profit, Jhpiego, is an attempt to provide a low-cost digital alternative to the paper-based partograph [143]. Three E-Partogram designs are currently being developed, including an Android tablet application, a digital clipboard system, and a custom hardware solution. At this time, testing and evaluation of these implementations has not yet been conducted. While technical solutions may overcome several barriers that static paper forms cannot, some of the potential drawbacks of deploying a digital system in rural or low-resource areas include intermittent power and connectivity, low literacy levels, low levels of technical training, and maintenance and scalability costs.

2.5.6 Partograph Evaluation Methods

In order to determine the effectiveness of the partograph, prior studies have used several different ways of measuring the "completeness" of partographs in relation to various outcome variables. Kenyatta National Hospital uses a coarse-grained grading rubric internally to quantify

the utilization of the form (see Figure 19 in Chapter 4). Completeness criteria include 'correct' or 'incorrect' and 'complete' or 'incomplete' for each partograph section (i.e., fetal heart rate, cervical dilation, etc.) including the summary sections at the bottom of the form. This rubric, while good for producing estimates of partograph use, is subjective, and does not reflect whether the partograph is being used *as* intended or if the form contains accurate information about the labor. Also, this rubric does not provide any insight into how the patient was cared for under different circumstances based upon the data recorded on the partograph.

Researchers interested in partograph completion and its affect on maternal outcomes have taken a more fine-grained approach to evaluating form 'completeness'. A 2013 study by Lavender et. al. evaluated the impact of the WHO e-learning tool on partograph completeness among nursing students [144]. Researchers used a before-and-after study to determine how the introduction of the e-learning tool affected nursing students' ability to complete a partograph form correctly. This study did not illustrate major improvements in partograph completion between students who did and did not use the e-learning tool. The authors concluded that the partograph may be too complex, and that it requires simplifying modifications, in addition to training tools like the e-learning tool to be as effective as possible. The authors also stressed the need for clinical experience and positive role models in the clinic for nursing students in order to put knowledge into practice with partograph use. Using the key conclusions from this study, the PartoPen is designed for use in both clinics and classrooms in order to bridge the gap between knowledge and practice, and provide a transitional tool that assists in reinforcing the training students have received when they are in a clinical environment.

In a 2011 study by Rotich et. al., researchers observed women in labor and midwives at Kenyatta National Hospital and Moi Teaching and Referral Hospital. Only women in active (i.e.

cervical dilation of 3cm or greater) normal labor were observed during the study. Researchers in this study were physically present to observe all the labors included in the study results, and they recorded observations about how the partograph was used during each labor. This study revealed that 'molding' was rarely assessed or recorded on the partograph, and the bottom third of the form (temperature, respiratory rate, and urinalysis) was very rarely assessed and thus not recorded. A benefit of this evaluation approach is a more accurate account of how accurately the partograph was filled out, because the researcher was able to observe the measurement being taken, and whether that measurement was correctly recorded on the partograph in real time. Additionally, researchers were able to see if correct interventions occurred as a result of the data recorded on the partograph. However, this approach is time-intensive, and may introduce significant observer bias because researchers were physically present and watching during the labors and measurement recordings.

A 2012 study by Margaret Khonje also attempted to evaluate partograph use and its affect on maternal and neonatal outcomes, using an alternative partograph evaluation scheme. Khonje's evaluation method only considered whether measurements had been made for each partograph section, using a yes/no data-gathering sheet. Supplemental data were collected on how many times a certain measurement had been recorded, but these data were not compared to any baseline expected value. Partographs were deemed 'complete', 'incomplete', or 'blank'. Then, partographs were further categorized as 'OK', 'adequately filled in', 'inadequately filled in', or 'grossly inadequate', based on how many of the partograph section groups (i.e., fetal monitoring measurements, the cervicograph measurements, or the maternal monitoring measurements). This grading scheme is fairly coarse-grained, similar to KNH's internal evaluating rubric, but

provides a second level of categorization that attempts to understand how useful the partograph is in addition to its completeness.

2.5.7 Summary

Understanding barriers facing partograph use, and the limitations facing low-resource areas, is an essential first step in effectively addressing the low rates of partograph completion and use. Effective partograph initiatives need to be cost-effective, intuitive, need to promote training and ongoing education, and must work within the complex set of issues contributing to staff and supply shortages in developing countries.

The PartoPen project attempts to provide a low-cost, intuitive solution to many of the barriers facing effective partograph use in the developing world. By using digital pen technology, and enhancing, rather than replacing, the paper partograph system already in use, the PartoPen project addresses training and point-of-care issues without introducing significant training or financial costs. This chapter has illustrated several important areas of prior work in international development, maternal health, information and communication technologies for development, digital pens, and the partograph.

3. THE DESIGN AND IMPLEMENTATION OF THE PARTOPEN SYSTEM

Digital pen technology, as we have seen, has been evolving for several decades. Each iteration of this technology has sought to create a stronger link between the fluid and intuitive action of writing with pen and paper, and an increasingly digitized world. The PartoPen project chose to use a Livescribe (LS) digital pen, mainly because of its audio recording and playback capabilities. This chapter describes the technical aspects of the LS digital pen hardware, the Anoto dot pattern paper used by LS, and the other hardware and paper components used by the PartoPen system. The chapter concludes with a discussion of the unique technical contributions of the PartoPen project.

3.1 Livescribe Digital Pens and Anoto Dot-Pattern Paper

The current implementation of the PartoPen system uses the Livescribe (LS) Echo digital pen. The Echo pen (see Figure 9) has a built in microphone, speaker, and an OLED display. The pen uses a rechargeable lithium ion battery, which is advertised to last about 36 hours during normal use. We have observed a battery life of about 20 to 26 hours, depending upon the amount of audio played during that time. Pens can store between 200 and 800 hours of audio, depending on the pen model, and all stored data can be downloaded to a desktop computer using a standard micro-USB cable.

Figure 9: The Livescribe Echo digital pen. The pen includes a speaker, microphone, OLED display, USB connector for charging and data transfer, and audio jack for headphones, 2-8GB of memory, and a replaceable ink tip.

The Anoto "dot pattern" (see Figure 10) used by LS pens employs an invisible grid system. On each sheet of paper, each gridline is spaced 0.3mm apart. At each grid intersection, a microdot is printed on the page slightly offset in one of four directions – up, down, left, or right of the intersection itself. Each dot thus encodes two bits of location information based on its location relative to the grid and relative to the dots around it. The digital pen tip contains an infrared camera that captures between 70 and 100 snapshots per second of these 6x6 grids of dots (i.e., each photograph contains 36 dots). The X and Y coordinates represented by the dots in the photograph are translated and interpreted by the digital pen, and are mapped onto a specific page address in the Anoto pattern space. The entire pattern space covers an approximate area of 4.6 million km^2, which represents roughly 73 trillion unique sheets of letter-sized paper [86]. Using

this technology, the LS digital pens are able to interpret where on a page the pen-tip is at all times, and can therefore recreate ink strokes from the stored coordinate data.

LS pens differentiate between two types of pattern space – open paper and fixed print regions. Open paper is designed for free-form note taking and drawing, whereas fixed print regions are visibly defined on the page, e.g., as buttons, and provide specific functionality such as menus or audio controls. The PartoPen system uses standard button-like fixed print regions for accessing use instructions, but also extends the fixed print paradigm by implementing user-generated fixed print regions. For example, a user might plot a measurement with an 'X' on the graph. The PartoPen system takes the users' handwritten 'X' and interprets this symbol as a fixed print or dynamic area that will now function as a button that can be tapped to initiate some action. This functionality will be described in more detail in the explanation of the PartoPen decision support mechanism.

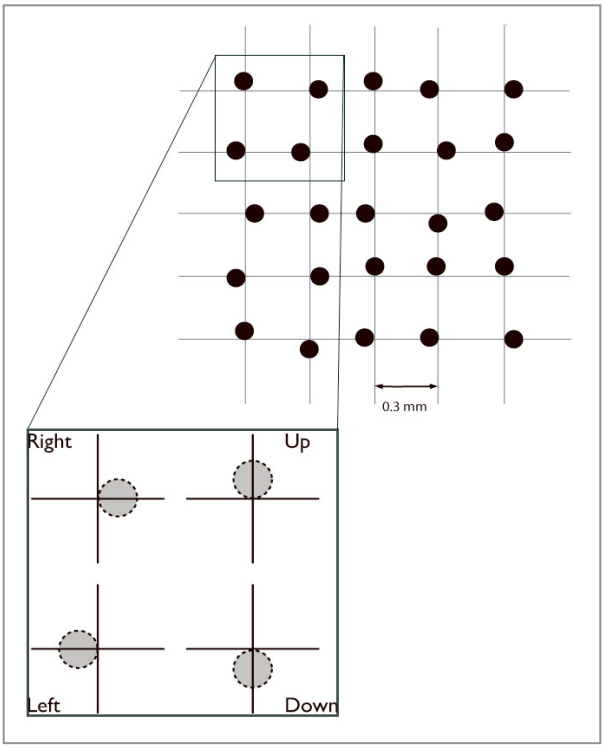


Figure 10: The dot pattern, patented by Anoto AB Group.

The LS pen SDK provides a tool for creating custom "paper products," which, in the case of the PartoPen, is the partograph form (see Figure 11). To design a custom paper product, a developer imports images (in this case, the standard WHO partograph) and defines regions on this image that will trigger a response from the digital pen. In the "penlet," or digital pen software program, the developer defines the functionality that is activated when the digital pen writes in these regions. Touching the pen-tip to the paper will trigger a "pen down" event, and execute the program code associated with that area on the page.

The LS digital pen was chosen as the PartoPen platform because of its unique abilities to record and playback audio, and synchronize audio with handwritten text. The PartoPen system utilizes the audio output capabilities of the LS digital pen, but does not incorporate audio recording and synchronization into its functionality. LS digital pens, like other digital pen models, also create searchable, digital copies of handwritten notes in a desktop-based software application. Early on, the availability of the LS SDK allowed for rapid development, deployment, and iteration of the PartoPen system, as well as documentation and a developer community. Livescribe formally discontinued its development program in July 2011, but continued to work with PartoPen researchers to facilitate ongoing development and implementation of the PartoPen system.

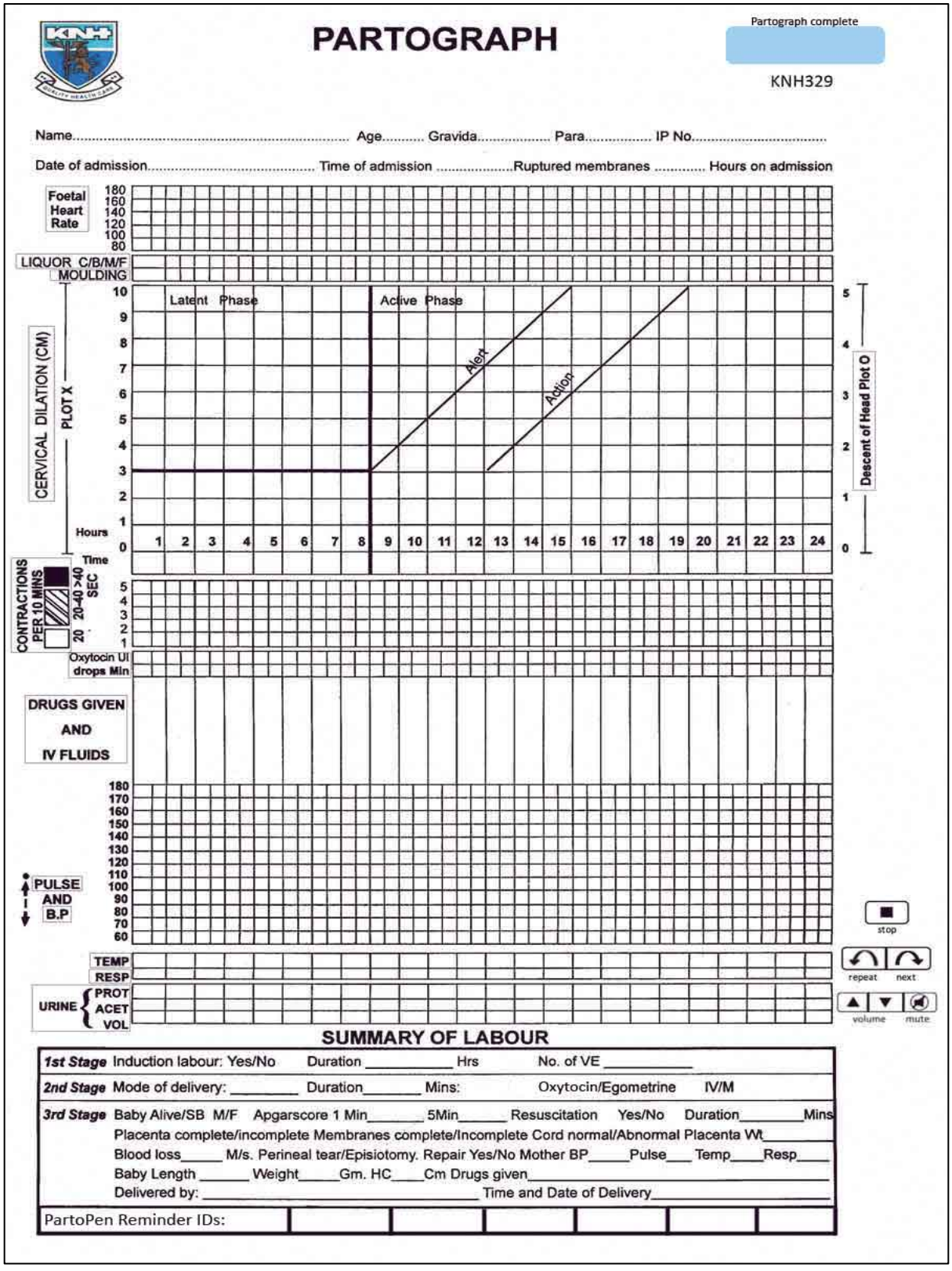


Figure 11: The revised PartoPen partograph. PartoPen Reminder ID boxes, audio controls, and a partograph complete box were added in addition to boxes around some of the existing text.

3.2 PartoPen System Software, Design Iterations, and Rationale

LS digital pen software (a "penlet") is activated when the digital pen makes contact with paper printed with a dot pattern. The "pen down" event that triggers the PartoPen application initiates three simultaneous events, as shown in Figure 12.

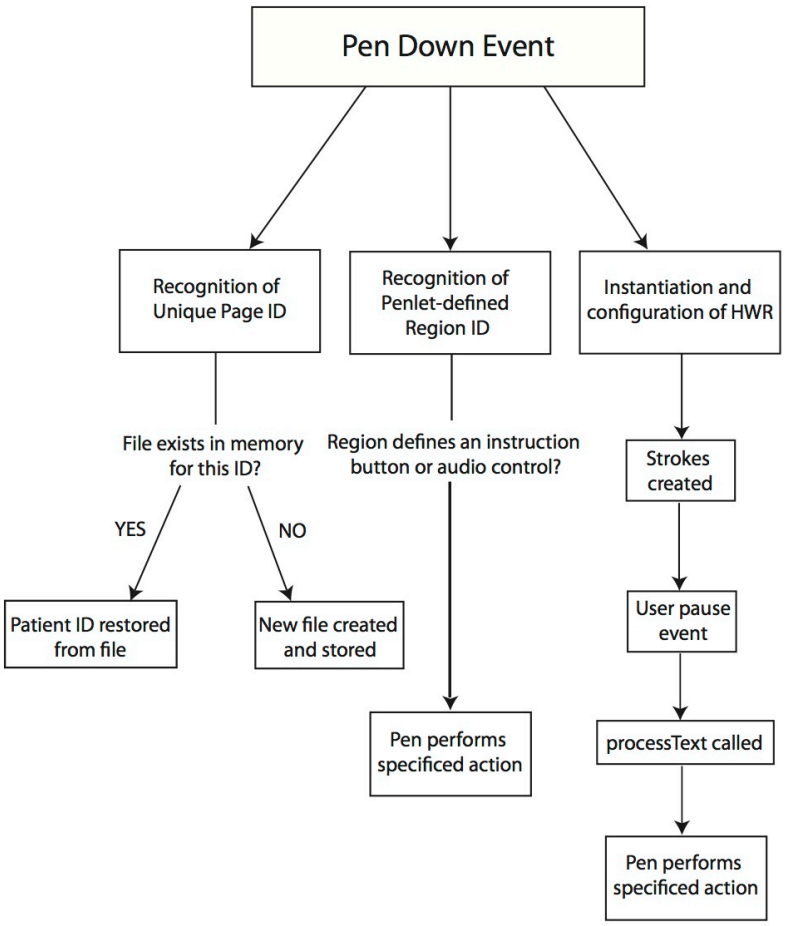


Figure 12: PartoPen software execution path. Illustrates the events triggered when a PartoPen first touches a partograph form.

First, the pen retrieves the unique page ID encoded on the form, and attempts to locate a file in internal penlet storage corresponding to that page ID. If a file for that page exists, this indicates that this pen has been used with this form in the past. If a file is not found, it is assumed that this is the first time this pen has been used on this form, and a file is created in internal

storage. The information stored in this file, if it exists, is a string that maps the unique page ID to a human-readable, user-generated patient identifier (i.e., patient initials, name, room number, etc.) Patient identifiers are used by the reminder system to give nurses patient-specific, rather than general, reminders. This file storage and patient ID retrieval system is described in more detail in Section 3.5.

Second, the pen retrieves the region ID. The software determines the correct pen output based on where the user has tapped or written data on the form by using this region ID. Any region designed to produce pen output (instruction buttons and audio controls) corresponds to a delegate method in the code that executes the correct program functionality.

Finally, the initial "pen down" event activates the hand writing recognition engine, which is used to process handwritten input. The handwriting recognition engine is instantiated with a general text resource package. The PartoPen software adds an additional resource package containing a custom lexicon of common user input for the partograph form, which improves the handwriting recognition of the application. The handwriting recognition engine, once initiated, waits for a "user pause" event, the length of which is determined by the developer before compiling. The PartoPen currently uses a one second user pause time. A "user pause" event calls the "processText" method, which in turn initiates the appropriate program flow based on text input and region ID.

The implementations of the three main PartoPen components – use instructions, decision support, and reminders – are described more fully in the following sections.

3.3 Use Instructions

One of the goals of the PartoPen system is to reinforce birth attendant training on correct use of the partograph, as this has been cited as a significant barrier to consistent use of the form. The

WHO partograph user manual and a local partograph manual issued to clinics by the Kenyan Ministry of Health are the primary resources for partograph instruction in Kenya. These manuals, however, are not generally portable, and are not easily located or utilized in busy labor wards. The PartoPen system makes the instructions found in these manuals accessible directly from the partograph itself. The PartoPen uses fixed print "button" regions around the partograph text to provide verbatim audio recordings of the instructions found in the partograph use manuals. Thus, by tapping on these "buttons," nurses and nursing students can get short informational prompts on how to use each section of the form correctly.

The audio for each partograph section (e.g., fetal heart rate, contractions, etc.) is divided into short prompts less than 20 seconds long. By tapping the button a second time, users hear the second prompt, and so on until all of the instructions have been played and the first prompt in the series repeats. The audio prompts are organized such that well-trained nurses can quickly access the high-level "refresher" prompts with only one or two taps, while students or new nurses can explore additional details of correct partograph use by tapping repeatedly on the same button.

Based on user observations and feedback, several modifications were made to the instruction audio prompts. First, tapping multiple times on the same button to access the next instruction prompt was not intuitive. To address this issue, the audio prompts were re-recorded to include the phrase "tap here again to hear more instructions" at the end of each prompt. However, it was found that using this phrase made users feel like they *had* to tap the button again even if they weren't interested in hearing more instructions. The audio was therefore reverted back to the original instruction prompts, and a new fixed print "next" button was added to the partograph form itself. Users indicated that having a separate audio control on the page specifically for advancing the instruction prompts was much more intuitive, and researcher

observations supported this finding. A “repeat” button was also added to the form during this iteration after nurses complained of having to tap up to ten times to hear the same audio prompt again. The repeat button was an important (and retrospectively obvious) feature that was immediately and consistently used by nurses in the teaching scenarios.

Based on nurse feedback, future iterations of the instruction audio will be recorded by a local nurse or doctor to address the accent problem reported by some participants. Native speakers of multiple languages and dialects can quickly and easily record the audio prompts – a process that will be performed depending upon future interest and deployment locations of the PartoPen. The simple recording process will also allow the software to easily adapt to WHO or local health ministry changes to standard partograph protocols.

3.4 Decision Support

One of the most commonly cited barriers to partograph use is the inability to interpret the data plotted on the partograph and take appropriate action. Nursing students and less-experienced nurses often plot the data correctly on the partograph, but fail to derive the meaning of the plotted data, or do not remember what actions to take based on the data that they have plotted. The decision support functionality of the PartoPen addresses these issues by interpreting plotted data based upon page location, and providing real-time feedback on the appropriate actions to take. Currently, the PartoPen provides decision support in three of the partograph sections: cervical dilation, liquor/amniotic fluid, and fetal heart rate.

The cervical dilation versus time graph has two decision support lines: the “Alert” line and the “Action” line. Normal labor measurements are generally expected to stay on or to the left of the “Alert” line. If a measurement is plotted between the Alert and Action lines, the WHO protocol for the management of labor suggests several actions that should be taken for this

patient. The "Alert" line was originally added to the partograph to provide an indicator of when to transport a woman to a facility that could provide emergency cesarean sections. Thus, in the event that the next measurement reaches the "Action" line, the patient can receive necessary care at an appropriate facility. Timely decision-making based on the cervical dilation measurements can be life-critical. The PartoPen system attempts to improve the speed of this decision-making process by immediately calling attention to a concerning measurement and suggesting appropriate actions. On the cervicograph section of the PartoPen partograph form (see Figure 13) four regions are defined: above the latent phase line (black), normal labor (blue), between alert and action lines (green), and across the action line (orange). Any measurement plotted above the latent phase line should be transferred onto the Alert line and the current clock time should be written below the measurement on the Alert line. Therefore, if a nurse plots a measurement in this area, he or she will hear the decision support tone from the pen and the following text will scroll across the pen display: "Transfer measurement to the Alert line. Patient is now in active labor." When a measurement is plotted in the second region – the triangle to the left of the Alert line indicating normal labor – no response is triggered from the pen. Measurements plotted in the region between the Alert and Action lines will trigger the decision support tone again, and suggested actions will scroll across the display. The region to the right of the Action line also responds to pen events by playing the tone and scrolling the suggested set of actions appropriate for that measurement. All of the recommendations provided by the PartoPen were taken from the WHO manual on partograph use [145].

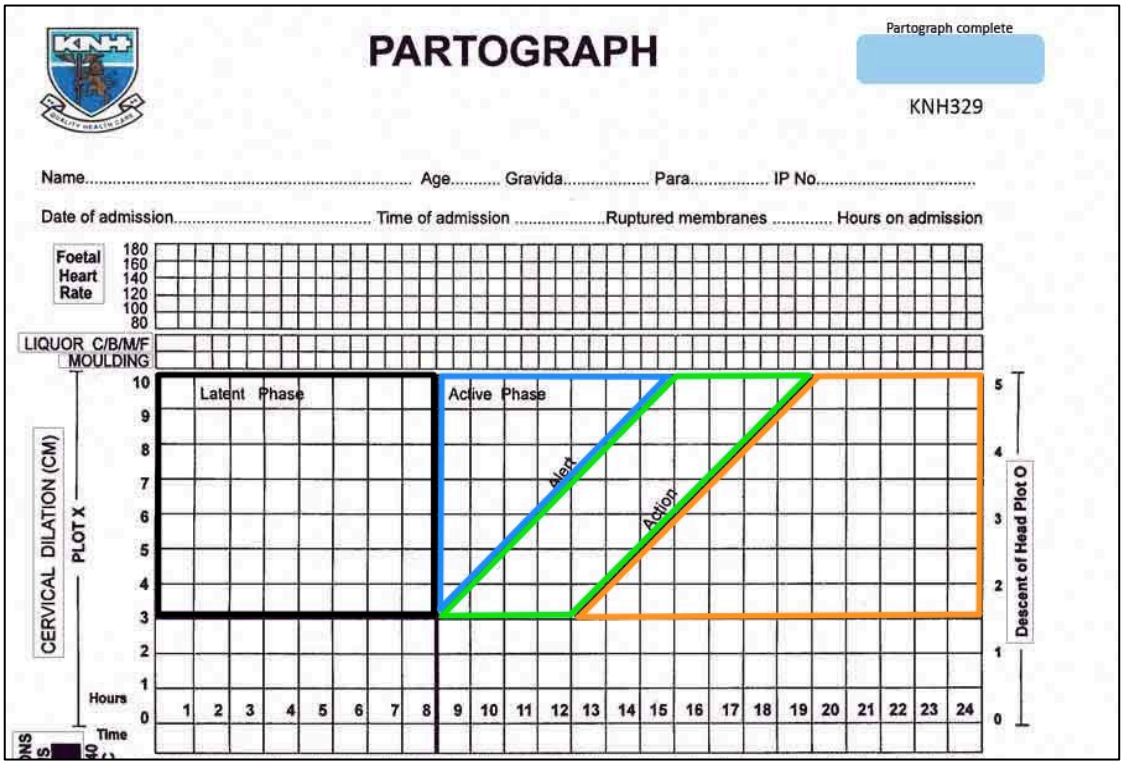


Figure 13: The cervicograph section of the PartoPen partograph. The box farthest to the left is outlined in black, representing the latent phase area; the triangle next to the black box (outlined in blue) represents 'normal' labor progression; the parallelogram between the alert and action lines is outlined in green; and the trapezoid on the far right is outlined in orange, and represents prolonged labor.

One particularly confusing aspect of the standard partograph form is that cervical dilation and descent of the fetal head are plotted on the same graph. Cervical dilation is plotted with an 'X', and descent is plotted with an 'O'. However, there are cases when an X and an O can be plotted in the same place on the graph, which requires the PartoPen to determine which measurement (either dilation or descent) is being plotted in order to produce the appropriate response. LS pens use third-party handwriting recognition (HWR) software, which is available for use in custom penlet applications like the PartoPen. In the initial implementation of the PartoPen software, the HWR software was used 'as-is' to differentiate between Xs and Os on the graph. However, the LS HWR software is configured to interpret all alphanumeric characters and

most UNICODE symbols. The HWR software often interpreted Xs and Os as other characters or symbols, which exacerbated the challenge of differentiating between Xs and Os. To address this problem, a custom classifier was built, which takes the first character in a HWR string (to ensure only one letter is being used) and compares it to an array of letters, numbers, and symbols. The entries in this "X array" are characters that were often returned instead of an 'X' when an 'X' was in fact written. If the character does not match any of the entries in this array, an 'O' is returned. After implementing this classifier, recognition of Xs and Os was near 100%, and only one or two instances of misrecognition were reported during the entire study.

HWR software is also used to provide the decision support for the liquor/amniotic fluid section of the partograph. This functionality was added during the first week of the study, after nurses consistently emphasized the importance of this particular measurement when determining the status and health of the fetus. Four possible entries can be made for this section: 'I' (intact), 'C' (clear), 'A' (absent), or 'M' (meconium stained). These data represent the state of the membranes and the color of the amniotic fluid. Meconium (excrement of the fetus) stained fluid is a reliable indicator of fetal distress, which necessitates an expedited delivery to ensure the health of the fetus. The PartoPen uses HWR software and another custom classifier to differentiate between 'M' and every other character. If an M is recognized, the pen plays the decision support tone and text scrolls across the OLED display indicating fetal distress, and suggests appropriate next steps.

The partograph section for recording fetal heart rate (FHR) was also decision-support-enabled. A normal fetal heart rate, as defined by the WHO, is between 120 and 160 beats per minute. The Kenyan Ministry of Health uses a national standard of 110 to 170 beats per minute. Initially, the WHO standard was used for PartoPen decision support in this area; however, it was

changed a few days into the study to adhere with the nationally recognized rate. Fetal heart rate is recorded with a solid dot, and each dot is connected to the preceding dot with a solid line, which creates a graphical representation of heart rate over time. If a fetal heart rate above 170 or below 110 is recorded on the graph, the decision support tone will play and text will scroll across the pen's OLED display indicating potential fetal distress.

In the first implementation of the PartoPen system, the decision support functionality used pre-recorded audio prompts similar to the use instructions. Observation of the pen use in the labor ward prompted several design changes. First, the audio was often too quiet for nurses to hear it in the generally loud labor ward environment, even with the volume turned up all the way. Second, the audio prompts, which were recorded verbatim from the WHO manual, often contained words or phrases that, when played in front of patients, caused concern. Finally, at KNH, one of the busiest hospitals in Kenya, patients rarely have their own room, and often share rooms with two or three other women (despite there only being two beds in each room). When two nurses were completing partographs for two different patients in the same room, the decision support audio prompts that would play overlapped and were incomprehensible. In light of these environmental challenges, a short, unique audio tone was created and the audio recording was replaced with scrolling text on the pen's OLED display. During the study, the tone proved generally adequate for drawing nurses' attention to the data they had just entered on the partograph. However, in some cases, the scrolling text was reported to be hard to read, and some nurses did not look at the display after the tone played.

Decision support was limited to the three partograph sections described above – cervical dilation, liquor/amniotic fluid, and fetal heart rate – largely because of the variability and scarcity of labor management protocols and suggested actions for other partograph sections, and also

because of certain technical challenges associated with identifying and interpreting hand-drawn patterns (slashed lines, colored boxes, etc.). Future additions to the decision support functionality should be based upon feedback received during follow-on studies.

3.5 Reminders

The labor ward at KNH delivers approximately 1000 babies during the "busy" months from October to March, or roughly 34 babies every day. On average there are 4-6 nurses working at a time, and based on survey data collected at the end of the PartoPen study, nurses on average are responsible for 5-7 patients during a day shift and 7-10 patients during a night shift. The WHO recommends a maximum ratio of 1 nurse to 3 patients to ensure compliance with partograph completion protocols. When surveyed, nurses almost unanimously reported that staff shortage is the most common reason for low partograph completion rates. While the PartoPen does not replace nurses or supplement the shortage of nurses in the labor ward, it provides a reminder system intended to help busy and tired nurses keep track of when patients need measurements taken.

In general, measurements on the partograph are either taken every half hour, or every four hours. For example, fetal heart rate is recorded every half hour and cervical dilation is recorded every four hours. In theory, all of the half-hourly measurements should be taken during the same half-hourly exam; the same is true for all of the measurements taken every four hours. Using this information, fetal heart rate and cervical dilation measurements drive the half-hourly and four hour reminders, respectively, for all measurements in these time brackets. For example, if a nurse only plots pulse (a half-hourly measurement) on the partograph without plotting fetal heart rate during the same exam, he or she will not receive a reminder in half an hour. The decision to implement the reminders in this way was designed to reduce the number of reminders

a nurse would receive for a single patient, as nurses are already caring for more patients than is recommended during any given shift. A previous PartoPen study [20] showed that nurses can quickly become desensitized to pen output if audio is frequently emitted from the pen. Using fetal heart rate and cervical dilation as the reminder drivers was based on data from a 2011 study that identified these partograph sections as the most commonly filled out, with fetal heart being filled out 90% of the time and cervical dilation being plotted 97% of the time [7].

One nurse midwife with over 20 years experience pointed out a unique case that can arise from using fetal heart rate as the half-hourly reminder driver. In the unfortunate case of an intrauterine fetal death (IUFD), there will be no fetal heart rate to record, but other measurements will be recorded on the partograph because the woman still goes through labor to deliver the dead fetus. Researchers suggested making a straight horizontal line on the fetal heart rate graph to initiate the reminder, but a more appropriate solution has not yet been developed.

Reminders are implemented using separate timer threads that get created every time a nurse plots a fetal heart measurement or a cervical dilation measurement on the partograph. The timer uses a patient identifier that corresponds to the unique page ID encoded in the dots on the form. When the timer thread runs, the reminder tone (distinct from the decision support tone) is played, and the patient ID scrolls across the OLED display along with a summary of the measurements that need to be taken at that time. If the nurse has not entered a patient ID, or the pen has failed to capture an entered patient ID, a general reminder message scrolls across the screen indicating the measurements that "a patient" needs attention at that time.

3.6 Reminder Patient IDs

The initial PartoPen implementation attempted to use the HWR engine to capture the patient name as a string, and use this as the patient identifier corresponding to that unique page.

However, observations and user feedback made it apparent that the HWR software did not reliably interpret patient names, and the one second user pause time did not allow for nurses to write a patient's name normally. This design resulted in nurses tracing a patient's name several times to get the HWR software to accurately capture the input, which often made the patient name unreadable on the actual form.

The second implementation of the patient ID system was a change to the instructions nurses were given rather than a change to the system itself. Nurses were instructed to write the patient name as usual, and then write the patient's initials directly after the name. Every time a nurse would write in the patient name field, the previous patient ID would be overwritten, thus if the patient initials were written last, these would serve as a simple yet identifiable way of determining to which patient the reminder was referring. While this approach addressed some of the HWR issues, because not as many characters needed recognizing, timing problems were still an issue, and nurses did not like the way it looked on the form. The nurses also expressed concern with this system during shift changes, for two reasons. First, a nurse could receive the same pen that was used on a patient's partograph in the previous shift, and therefore would receive any scheduled reminders for this patient. The problem with this scenario is that the patient ID (i.e., the patient initials) is not a sufficient identifier for a nurse who did not initially write them. Thus, nurses in this scenario are no better off than a nurse receiving a generic reminder from the pen. The second scenario is when an incoming nurse receives a new pen that has not yet been used on her patient's partograph, but the partograph has already been partially completed by the nurse on the previous shift. In this scenario the nurse will not receive any of the previously scheduled reminders for this patient (because they have a new pen). If they want to receive future reminders for this patient, they must trace over the patient initials to store that

patient ID in this new pen. Again, this is non-intuitive, and creates a messy looking, potentially unreadable form.

The current (third) implementation of the patient ID system uses a row of boxes titled "PartoPen Reminder IDs" below the summary at the bottom of the partograph form (see Figure 14). Nurses use these designated boxes to create a patient ID of their choice. Nurses often used room number or patient initials as the patient ID. This implementation solves the HWR issues described above, separates the patient IDs from the standard patient information fields, and provides multiple ID boxes so that an incoming nurse working on a partially completed partograph with a new pen can create his or her own identifier for this patient in a new box.

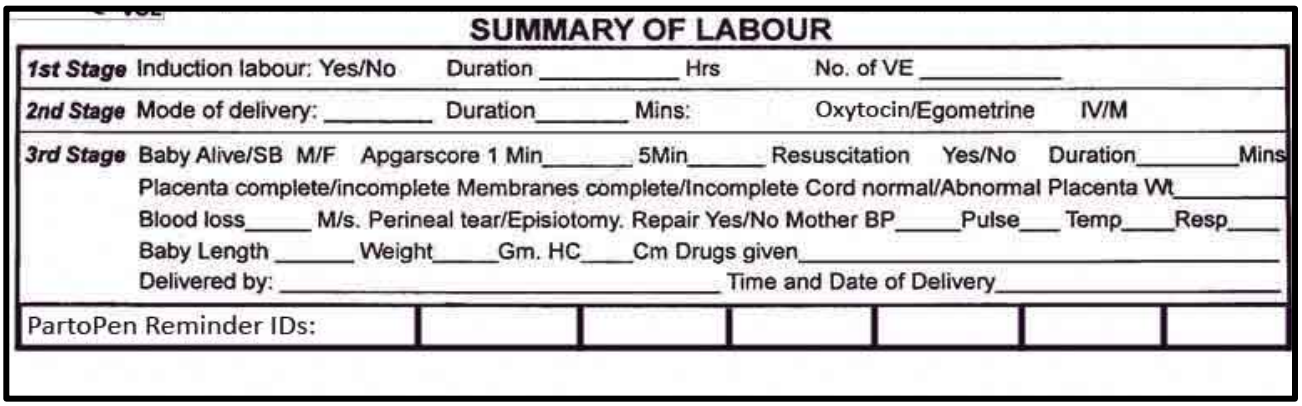


Figure 14: A close up of the PartoPen Reminder ID boxes at the bottom of the partograph form underneath the summary of labor section.

At the beginning of the study, researchers did not insist that the PartoPens be handed over to the nurse on the next shift who was taking the current nurse's patients. However, nurses found that this was a much more intuitive (and sustainable) way of handing off the pens, rather than obtaining a new pen from researchers at the beginning of their shift. In addition, the reminders that had been set for a patient by a nurse on an earlier shift would then carry over to the nurse on the next shift who was now taking care of that patient. There were several times when

researchers observed nurses starting a shift, receiving their pen from the nurse on the previous shift, and shortly thereafter, receiving a reminder from the pen to attend to a specific patient that they had not yet checked on. This system created a level of continuity in patient care that had previously been absent in the KNH labor ward during nurse shift changes.

Another possible way of implementing the patient identifier system is to use the audio recording capabilities of the pen to record a nurse saying a patient's name, and play that recording back when a reminder for that patient goes off. This design would avoid possible HWR issues, and create a more personalized way of creating patient IDs, but introduces some technical challenges including, but not limited to, simultaneous audio input and output (this is a known issue with LS pens).

As LS pen technology continues to develop, networking capability between pens is expected to become a standard feature. The ability for pens to communicate information over a local area network would allow future implementations to create reminders for specific patients to be transferred between pens, thus allowing each nurse to have his or her own pen and still get reminders that were scheduled for their patients during the previous shift.

3.7 Reminder Cancellation

During the first week of the PartoPen study, one of the nurses approached a researcher and asked why he was getting reminders for a patient that had already delivered. In the initial PartoPen design, there was no way to cancel reminders for patients once a partograph was complete. The work around for the remainder of that day was to turn the pens off and back on after a patient delivered or went for a cesarean section. This was a work-around because, not only did this action cancel reminders for the patient who had delivered, it canceled all reminders for all patients.

In order to allow nurses to cancel reminders, researchers modified the partograph form by adding a small blue "partograph complete" box in the upper right hand corner of the form. When a nurse completes a partograph for a patient who has delivered or gone for cesarean section, he or she uses the PartoPen to sign his or her initials in the blue box. When a "pen down" event occurs in the region encompassed by the blue box, the file stored on the pen corresponding to that unique page is deleted. When a reminder thread executes after waiting the specified 30 minutes or 4 hours, it will first check if the file corresponding to the reminder exists in internal penlet storage. If the file exists, the reminder is played, but if the file does not exist (i.e., it has been deleted by someone writing in the blue box for that page) the reminder does not play.

Adding the blue box to the form sufficiently addressed the reminder cancellation issue, but also had the unintended positive side effect of introducing accountability to the form. By signing their initials in the blue box, nurses acknowledge that they completed the form and monitored the labor. This accountability promotes an increased level of detail and attention to partograph completion and accuracy among nurses, and simplifies the work of hospital administration staff tasked with investigating potential malpractice and creating annual staff performance reports.

Nurses reported that the PartoPen reminder system was the most useful and helpful component of the device. It was also the component with the most technical and usability challenges. However, by making minimal changes to the standard WHO partograph form, the two main issues – patient reminder IDs and reminder cancellation – were addressed sufficiently for current use.

3.8 Design Considerations

The PartoPen functionality described in this chapter was designed and implemented to address the most commonly reported barriers to partograph use, and to ultimately improve partograph completion and accuracy rates.

From interviews with the nurses and researcher observations, the reminders issued by the PartoPen had the most impact on nurse behavior, although this impact did not translate into increased partograph completion for the reasons described below, and as discussed in more detail in Chapter 5. The goal of the reminder system was to ensure timely patient checkups by nurses who are busy, distracted, or simply have forgotten to check on one of their many patients. However, when the ratio of nurses to patients is between 1:5 and 1:10, even if a nurse has correctly recorded a reminder id and receives the patient's reminders, she may be assisting with another labor, checking on another patient, etc. Many of the nurses reported receiving the reminders but being unable to act on them because they were already involved with a different patient. Additionally, the design of the system was not as helpful to nurses who had their hands busy, as the patient code was displayed textually on the screen, and nurses were often unable to stop what they were doing to look at the pen and read the patient reminder ID.

There were also several aspects of the PartoPen design that focused on nurses' willingness to use the PartoPen and complete partographs. For example, the pen's OLED display was configured to return to the default screen, which displays the current clock time, after the nurses receive decision support or reminder text. Successful partograph completion relies on accurate recording of the time, and researchers frequently observed nurses using cell phones to check the time during patient exams. However, hospitals and clinics in Kenya are increasingly restricting the use of personal cell phones in the presence of patients to reduce distractions and to

improve patient care. By the end of the study, using the time on the digital pen display had replaced the practice of nurses using cell phones to get the current time.

As described earlier in the chapter, researchers made several modifications to the paper partograph form to facilitate PartoPen interaction. In addition to these modifications, the primary investigator recreated the partograph form using Adobe Illustrator to increase the size of the graphs and provide more room for nurses to write the measurements on the chart. In Figure 15 the original KNH partograph – a skewed, blurred, photocopied version – is shown. Figure 11 shows the revised PartoPen partograph form. Nurses reported several times that the nicer form was easier to see and more pleasant to use, and two nurses told researchers on separate occasions that they felt like doing a better job filling out the partograph to "keep it nice."

PartoPen project researchers did not at first recognize the importance of nurses' attention to detail and appreciation for keeping things neat and clean, but this realization significantly shaped several of the more subtle design decisions that were made during the study. Initially, researchers did not distribute the standard caps for the LS digital pens because they are difficult to get on and off, and are easily lost or misplaced. The nurses wore the pens around their necks using a lanyard researchers had attached to the pen. However, without a cap, the pens would occasionally mark the nurses uniforms, especially when nurses placed the pens tip down in their pockets. This prompted some nurses to discontinue using the pens altogether. After realizing the problem, researchers distributed caps (and left a supply of replacement caps in the labor ward) for the pens, resulting in increased PartoPen use among the nurses.

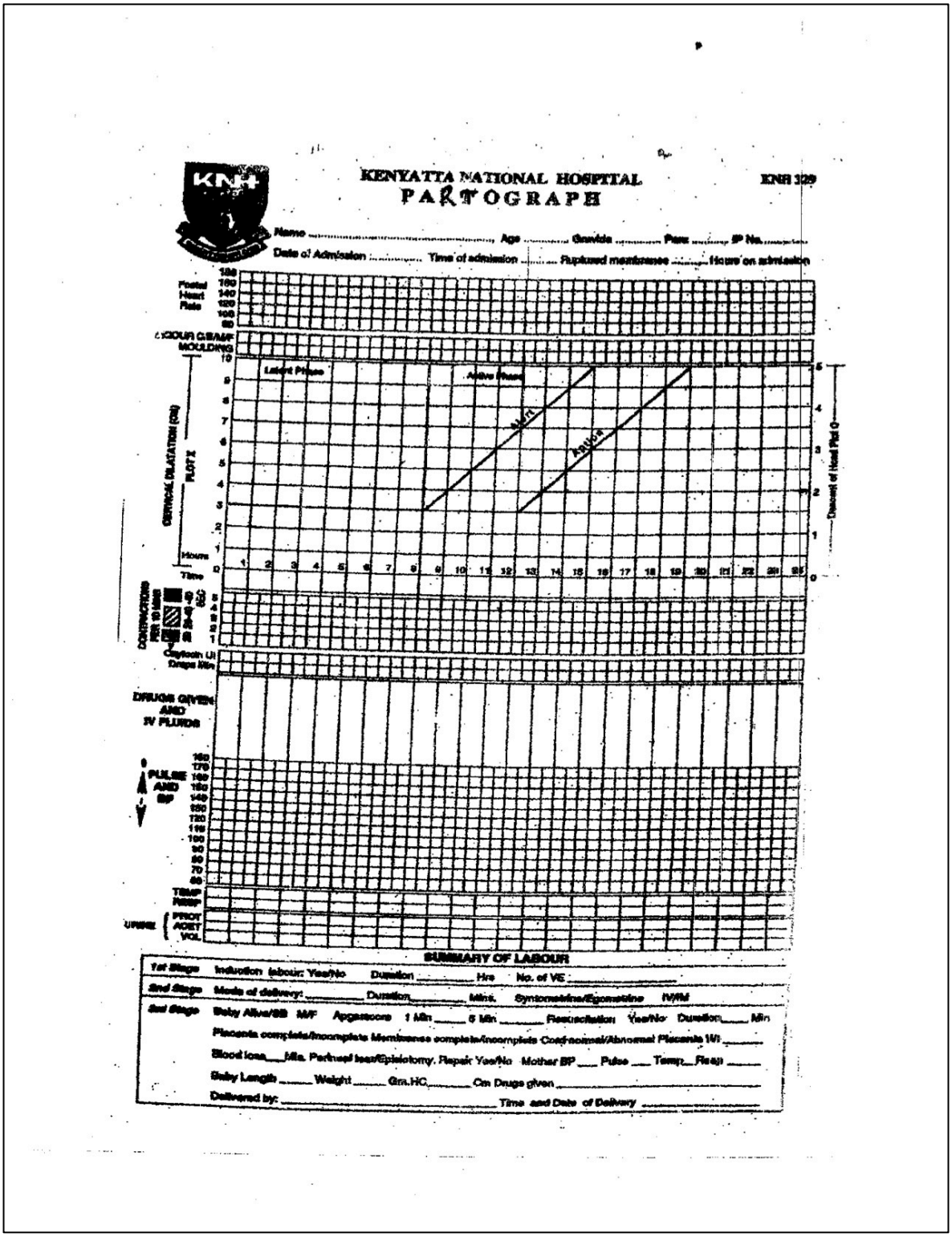


Figure 15: The original KNH partograph. Partographs were blurred and slanted due to multiple photocopying iterations.

3.9 Peripheral Technical Components of the PartoPen System

3.9.1 Desktop Logging Application

The desktop logging application was built to extract metadata from the PartoPen relating to the PartoPen software. During use, the PartoPen software logs every time an instruction button is tapped; when and where the user records measurements for fetal heart rate, liquor, and cervical dilation; and when reminders are set and are triggered. The desktop application was written in C# using a customized version of the Livescribe desktop SDK. The log file is extracted from the digital pen using a micro-USB cable that connects the LS digital pen to a computer running the Windows-based desktop logging application. The log is saved as a text file – one line per time-stamped log entry – and is named using the following convention: digital pen serial number, month, date range.

3.9.2 Nurse Perception Computerized Partograph Survey

A nurse perception computer survey was developed for the June 2013 follow-up visit to KNH. The survey is a locally running desktop application written in Java. The survey displays a split-pane application window with an anonymous KNH partograph image in the left frame, and five survey questions in the right pane (see Figure 16). The displayed partograph excludes both the patient's name and the 'Delivered By' nurse name from the partograph. The survey beings with an ID page that asks for the first three letters of a nurses' first name followed by the first letters of her last name. The text files produced by the computer survey are named according to the ID entered by the user. After entering an ID, the user is taken to the first partograph (of five), and can proceed to answer the survey questions pertaining to the partograph displayed on the left. Survey questions vary from multi-select radio button answers to single-select Likert scale responses. The survey content and results are discussed more fully in Chapter 4.

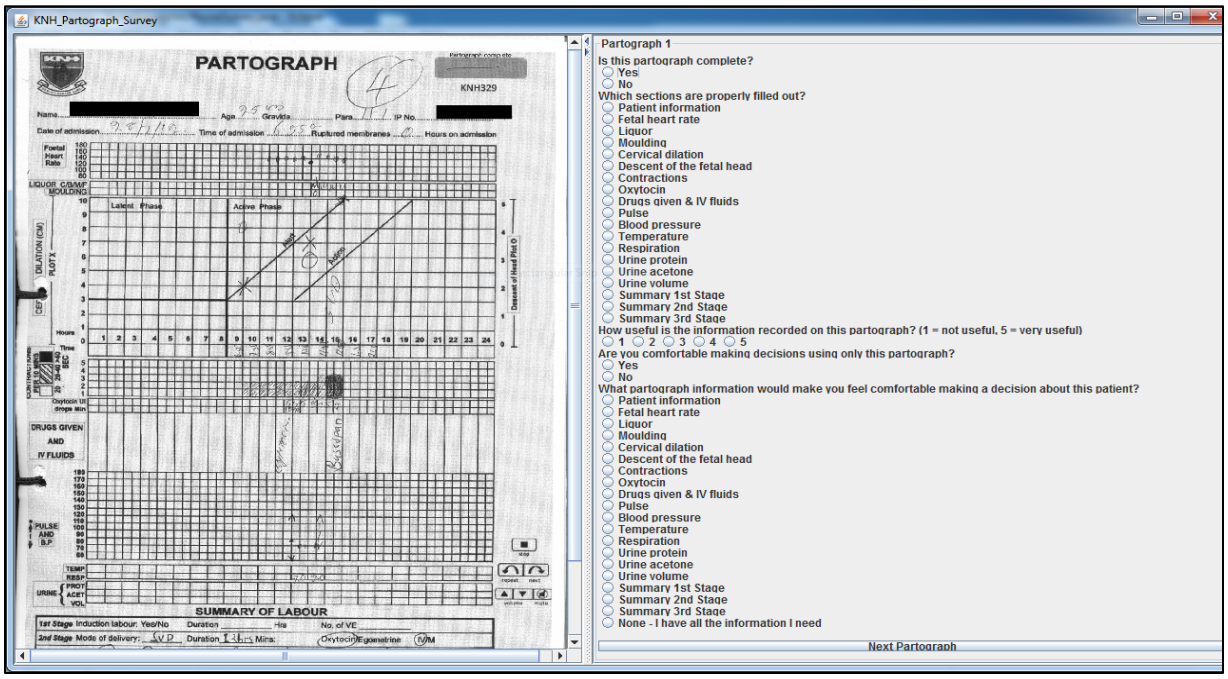


Figure 16: A screenshot of the computer survey used in the June 2013 Follow-up study. An anonymous partograph is presented on the left, and the five survey questions are presented on the right.

3.9.3 Printer Components and Considerations

The first printer that was purchased for the PartoPen studies was the OKI C610 printer. Anoto recommends a number of printers for printing the dot pattern pages, but the minimum stated requirements are: laser printer (although some ink jet printers in our experiments were successful), color (although some black and white printers successfully printed the dots), and 600 dots-per-inch (dpi) printing capabilities. A number of printers were used to print the dot pattern with varying degrees of success. Ink jet printers and black and white printers were occasionally successful, but required heavy pressure when writing to trigger the PartoPen functionality. The OKI C610 printer was reliable, included on Anoto's list of recommended printers, and was available from Copy Cat, the local printer store in Nairobi. A year after purchase, OKI printer replacement parts and toner were no longer available for the OKI C610 from Copy Cat. At the

time of the 2013 follow-up visit, KNH had acquired a new printer (HP LaserJet Pro 400 M451dn). However, KNH IT staff had been unable to successfully install the drivers for the new HP printer that enabled the PartoPen partograph dot pattern to print.

Several attempts at uninstalling and reinstalling the HP printer drivers on the records office computer, which ran Windows 7, revealed a repeatable problem. When running the HP installer, after being asked to connect the printer to the computer, the installer would reach 99% completion and hang for several minutes before issuing a fatal error message that the installation had taken too long to complete, resulting in the inability to use the device. HP support forums clearly documented this issue, which was apparently common for HP laser printers and the Windows 7 operating system. The SmartInstall software on the printer is incompatible with Windows 7, and must be disabled from the printer's menu before using the installation CD to setup the printer. The steps outlined in this forum (http://h30499.www3.hp.com/t5/Printers-LaserJet/HP-LaserJet-Color-400-M451dn-Install-Problem/td-p/5806343#.Ud7ltT4_-3A) were also necessary for the installation to complete successfully. The steps outlined in this link remove all previous installed drivers from past, failed installation attempts.

At first, the installation CD for the HP printer was not in the records office, and none of the staff had seen it when the printer was delivered. After a meeting with the head of the IT department, the printer software was located, and the drivers for the HP printer were successfully installed. In addition, the head of the IT department set up a reoccurring purchase order to keep the records office supplied with toner and paper for the printer, as the original discontinuation of PartoPen use was a result of the printer running out of toner and replacement toner not being delivered in a timely manner. The reoccurring order was placed for five units of each color toner four times a year for the next two years. This cost will be included in the $35-million (USD) plan

to transition KNH to electronic medical records, ordering systems, and patient intake. The addition of the toner order was considered to be a minor expense, and will be easily covered in the new budget allocated to technology-related expenses.

4. EVALUATION OF THE PARTOPEN SYSTEM

Four PartoPen studies were conducted between March 2012 and June 2013. The first study, a usability study at Kenyatta National Hospital (KNH), was conducted in March of 2012. The goal of the usability study was to evaluate a PartoPen prototype with nurses in the labor ward at KNH. During this study, the PartoPen design was refined, and the environmental and occupational workflow of the hospital was observed at length in order to inform the design and implementation plan for subsequent studies. The second study was conducted in June 2012 with nursing students at the University of Nairobi (UoN) School of Nursing Sciences, which is closely affiliated with KNH. The goal of this study was to evaluate the PartoPen system as an in-class teaching and training tool, and to conduct focus group discussions to gather students' opinions on usability and usefulness of the system. The third PartoPen study, conducted in July and August 2012, comprises the bulk of the PartoPen work to date. The PartoPen system was deployed and evaluated in the KNH labor ward as a pre- and post- study, where partograph completion was measured before and after PartoPen deployment. Surveys were also conducted with nurses, and informal interviews and observations were conducted throughout the duration of the study. The final study, in June 2013, was a follow-up study designed to evaluate the ongoing deployment of PartoPens at KNH after nine-months of use.

The Ethics Review Committee (ERC) at UoN and the Institutional Review Board (IRB) at University of Colorado Boulder approved the PartoPen research and study designs described in this section, and all relevant issues of informed consent were addressed prior to participation. This chapter describes the methodology and results of each of the four PartoPen studies.

4.1 March 2012 – Usability Study at Kenyatta National Hospital (KNH)

In March 2012, the first iteration of the PartoPen system was evaluated at KNH with nurses in the labor ward. The results and discussion of this study were presented as a full-paper and published in the conference proceedings of the 2012 IEEE Global Humanitarian Technology conference [22].

4.1.1 Study Site

The maternity wing at KNH contains 22 beds, but often holds upwards of 40 patients. Patients are separated into "normal" and "acute" rooms, based on whether pregnancy complications have occurred. The number of nurse-midwives per shift varies between five and ten; there are a total of 50 midwives who are employed in the KNH labor ward. The majority of the nurses are female. There is one OB/GYN physician who is on call throughout the day, as well as medical students who are completing their clinical requirements. The nurse-midwife community at KNH is close-knit, and the researchers observed that many of them arrive earlier and leave later than their shifts require in order to enjoy the evident camaraderie. These social times gave researchers additional opportunities to inquire about PartoPen use, while allowing the nurse-midwives to ask questions about the system and build rapport.

4.1.2 Methodology

During the one-week evaluation, six of the KNH labor ward nurse-midwives were interviewed and asked to complete a practice partograph worksheet with the PartoPen. The interviews and worksheet tasks were conducted with individual nurses as high patient loads made it impossible for nurses to participate as a group. Semi-structured interviews took place before and after the nurses completed the partograph worksheet. The pre-worksheet questions focused on current perceptions of partograph use in the labor ward, and the current issues nurses

experience when charting the partograph. The nurse-midwives then received a 10-minute demonstration of the PartoPen functionality, which highlighted key elements of the system's functionality, including audio decision support and time-based reminders. Participants were then asked to complete a worksheet by plotting sample patient data on the partograph using the digital pen. Each nurse completed the same "practice patient" worksheet, which illustrated a case of prolonged labor and subsequent labor augmentation or induction. This task took, on average, 15 to 20 minutes. After completing the worksheet, individuals were asked about the usability and practicality of the system. The entire process took 30-40 minutes.

The worksheets were loosely "graded" according to the WHO standards for correct partograph completion, but the primary goal of this evaluation process was to gain an initial impression of common partograph errors, not quantitatively evaluate partograph completion rates. In addition, researcher observations during the worksheet completion task were coded to determine the frequency of errors made by the PartoPen system. Rapid, iterative design changes were made to address observed PartoPen errors, and subsequent nurses used updated versions of the PartoPen software to complete the worksheet.

4.1.3 Perceptions of Current Partograph Use

The KNH nurse-midwives who were interviewed indicated that the number of patients per nurse-midwife ranges from 5 to 15, depending on the shift (night or day), and the month (some months typically have many more births than others). In contrast, the WHO recommends a maximum of three patients per nurse-midwife, so that patient measurements can be taken half-hourly, the time interval required by current partograph completion protocols. The high ratio of patients to nurse-midwives appears to be a primary reason for the low partograph completion rates observed at KNH. As two midwifes stated:

"When a midwife has more than three patients, she cannot take half hourly measurements for each one."
–Nurse-midwife at KNH

"It depends on the ratio of the patients you have. If you have more than three people in labor, you can't fill it." –Nurse-midwife at KNH

KNH is the largest referral hospital in Nairobi, and many patients are admitted to KNH after initial treatment at a district or regional level care facility. KNH nurses and doctors reported that the difference in the level of care available at satellite healthcare facilities often led to unmanageable complications after transfer to KNH. In addition, the partographs used at district hospitals are rarely sent with the patient due to district record keeping protocols. This imperfect referral system contributes to the low rate of partograph completion at KNH. The key suggestion by KNH doctors was for a referral system based on partograph data at the district hospitals, which would alert KNH to patients' conditions before arrival. A discussion of such a system using the PartoPen is discussed in Chapter 6.

The KNH medical staff also reported issues with partograph use. Several interview participants reported that less-experienced doctors, interns, and new nurses may make mistakes completing the partograph because they have been inadequately trained how to plot the data.

"Number one, you get new nurses coming to the labor ward who do not know how to use the partograph, so we have to educate them on how to use the partograph. Number two, you get students and they are using a partograph and they make mistakes. Even the doctors themselves, they do not know how to plot. They ask us." –Nurse-midwife at KNH

The current system for correcting errors on the partograph form is to replace the incorrect form with a new form, and re-plot the correct data, rather than correct the mistakes on the existing form. This practice can also contribute to low partograph completion rates and transcription errors. Despite these problems, the nurse-midwives were vocal advocates of the partograph:

"It is very helpful. We cannot do without the partograph. It is an important tool for monitoring labor."
–Nurse-midwife at KNH

"If it is used appropriately it is very helpful, but if you don't use it appropriately, it will not help you. I think it is helpful because you can make an immediate intervention just by looking at it. You just look at it and evaluate, and you take quick action." –Nurse-midwife at KNH

4.1.4 Pen Usability

Handwriting recognition and interrupted and repetitive audio prompts were the largest sources of PartoPen use issues during the worksheet completion task. Cervical dilation, plotted with an 'X' on the form, was at first incorrectly categorized by the digital pen 50% of the time, and repeated and interrupted audio had a desensitizing effect on participants, who started to ignore the audio prompts later in the task. To improve the handwriting recognition rates, a binomial classifier was implemented, which significantly reduced the number of incorrectly classified 'X's. Before the last two participants completed the worksheet, the code was modified to prohibit audio interruptions or repetitive audio within a certain time frame. The last two participants did not exhibit the desensitization observed with the first four nurse-midwives who completed the task.

A common practice during the worksheet completion task was for participants to think for several seconds before plotting data on the partograph. During the thinking interval, participants would rest the digital pen tip on the partograph form, which could trigger an unintended audio prompt. One participant was so distracted by the unexpected audio while he was thinking that he put the digital pen down, took a ballpoint pen out of his pocket, and used this pen to rest on the form while he thought about the measurement. Once he had finished thinking, he put the ballpoint pen back in his pocket and made the measurement on the partograph with the digital pen.

The nurses made several errors during the worksheet completion task, the most common of which was plotting the measurements on the incorrect vertical time line. Nurses would trace the vertical time line up and down the form to plot the measurements in the different areas of the form, but would often get interrupted or distracted in the busy labor ward environment. The non-intuitive time scale on the standard partograph is a significant source of user error.

The second most common error was incorrectly plotting the descent of the fetal head. The partograph used in the worksheet completion task was slightly different from the partograph currently used in the KNH labor ward, which was the primary reason for the errors when plotting this measurement. Currently KNH is transitioning to the newer WHO partograph, the version currently employed by the PartoPen system. Thus, in future studies at KNH, the errors associated with form differences should be reduced.

After participants completed the worksheet using the PartoPen, they were asked several questions about the system. One important finding is that the knowledge of the nurse-midwives at KNH exceeds the information currently available on the pen. Because of this, the PartoPen was seen primarily as an alert or reminder tool, rather than a source of useful medical knowledge.

"It alerted me that I had to take an action. The patient was going into distress. It is good for reminding even though I already know what to do." –Nurse-midwife at KNH

Participants were divided about whether the PartoPen would be helpful in managing the high patient load at KNH. One participant saw the audio reminders as being helpful because she sometimes gets overwhelmed when working with many patients, and the pen would help her remember.

"When working with many patients, it is easy to overlook things when you're overwhelmed. This would help even when you are overwhelmed." –Nurse-midwife at KNH

Another participant, however, saw the audio reminders as unhelpful, because with so many patients, she would not be able to respond to the audio reminders anyway.

"This would help, but you have to have a smaller number of patients. The way it's alerting you, we're observing after 30 minutes. It we have more than five patients we can't do it accurately. So I think it's helping you, but with a good number of patients." –Nurse-midwife at KNH

Other participant feedback focused on the physical characteristics of the digital pen. It was suggested several times that a lanyard was needed for the pen, and that a cap was necessary to keep ink from getting on their coats. One participant said the pen was a bit heavy, but she would still use it. Participants were also very interested in the durability, battery life, ink replacement aspects of the system, and the ability of the pen to correctly read a form that had been distressed (e.g., spilled on). Several durability studies, described in sections 4.4.3 and 4.4.4, were later conducted in the following months to shed light on the robustness and durability of the PartoPen system.

Overall, the perceived usability of the system was high. Participants were able to use the PartoPen without any training, and discovered the functionality of the system by using the partograph as they normally would. A two-minute tutorial was enough to explain how to turn the volume up and down on the pen, and how to access instructions if needed.

"I would use it all the time. It is easy to carry, and helpful." –Nurse-midwife at KNH

"This will go a long way in increasing our monitoring of patients with the partograph. It alerts you early, it alerts you on time, and it is just a normal pen." –Nurse-midwife at KNH

4.2 June 2012 – Nursing Student Study at the University of Nairobi (UoN)

Training and continuing education have been cited as serious barriers to nurses' willingness and ability to use a partograph form to monitor labor [137]. The nursing student PartoPen study examined the potential benefits of using digital pen technology with nursing students at University of Nairobi (UoN) School of Nursing Sciences. The goal of this study was

to evaluate the impact of the PartoPen system on students' abilities to correctly complete a partograph using case study patient data. The results indicate that the PartoPen system significantly improves student scores on partograph worksheets, especially for high-risk or complicated patient cases, which corresponds to cases with increased audio output from the PartoPen. These results suggest that partograph errors made by nursing students on rotation in the labor ward could be reduced if the PartoPen was employed in training and clinical use by students.

The work presented in this section was presented as a full paper and published in the conference proceedings of the 2013 Health Informatics conference held in Barcelona, Spain [21]. The paper presented at this conference was judged Best Student Paper, and was subsequently published in the "Communications in Computer and Information Science" (CCIS) series published by Springer-Verlag.

4.2.1 Methodology

In June 2012, the PartoPen was evaluated with 95 nursing students at the University of Nairobi (UoN). Students were asked to use a PartoPen in one of three modes to complete a partograph worksheet. In addition, students were asked to participate in a focus group discussion following the worksheet task. Local research assistants recruited participants from the population of 148 third and fourth year nursing students at the UoN. All participants had previously been taught how to use the partograph to monitor labor during a 10-15 minute in-class discussion as part of the nursing curriculum, and during their clinical rotations in the maternity wards.

The 95 student participants were separated into three groups. Group 1 was the control group; Groups 2 and 3 were the intervention groups, which focused on the discoverability of the functionality, and the affect on partograph performance, respectively. Group 1 students

completed a partograph worksheet task with a PartoPen in "silent logging mode," and received no instructions on how to use the technology. In the "silent logging mode" the digital pen recorded student answers, and logged when and where on the form student answers would have triggered feedback from a fully enabled PartoPen. This control group provided a baseline for students' performance on the partograph worksheet task.

Group 2 completed the same worksheet task, but used a fully functional PartoPen in "use" mode. The PartoPen software used for the student pilot had two key pieces of functionality: use instructions and decision support. For the nursing student study, the reminders (enabled only for the maternity ward study) were disabled. In addition, playing pre-recorded spoken audio provided the decision support, in contrast to the maternity ward decision support, which was provided by scrolling text across the OLED display.

Group 2 received no training on how to use the PartoPen. In "use" mode, the digital pen logged when errors were made on the form, which were compared to the baseline results recorded from the first class of students. Students in this group received audio feedback from the pen when data was entered incorrectly on the form, and thus, corrected errors were also recorded in this mode. The data collected from this group tested the discoverability and intuitiveness of the PartoPen functionality.

Group 3 received a fully functional PartoPen and a 15-minute introduction and demonstration of the PartoPen system before completing the partograph worksheet task. The digital pen recorded errors, corrections, and all marks made on the partograph form. By comparing the results of Group 3 with the results of Group 2, we were able to determine the effect of providing a PartoPen tutorial on partograph performance. Group 2 attempted to simulate PartoPen deployments in which students/nurses do not receive training prior to using the device.

Given that most of the PartoPen functionality is "pushed" to users during normal form completion, we hypothesized that training on the PartoPen system would not significantly alter the results of participants with the same level of prior partograph knowledge – Groups 2 and 3, respectively.

For each worksheet, students received two (of three possible) patient case studies. The three case studies represent three possible labor outcomes. Mrs. A's data represent an uncomplicated timely labor that progresses without medical intervention. Mrs. B's data illustrate a case of prolonged or obstructed labor, which is addressed by the administration of oxytocin, a labor-inducing drug, and results in a spontaneous vaginal delivery (SVD). Finally, Mrs. C's labor progression data illustrate an increasing number of complications, including fetal distress, and ultimately results in a cesarean section (CS). Thirty-four relevant instructional audio prompts were available for all students and all patient case studies. However, only the Group 3 students were informed how to access the instruction prompts by tapping the pen on the text to the left of the graphs on the form.

Following the worksheet completion task, students were asked to participate in a 15-20 minute focus group discussion on their experiences with the partograph and with the PartoPen system.

Quantitative results were obtained by grading the student worksheets and expressing "completeness" as a percentage of total correct partograph marks. For each case study in the worksheet, a certain number of measurements for each partograph section (e.g., fetal heart rate, liquor, molding, etc.) were expected. Correctness was measured by how many marks were recorded, if the measurement was recorded with the correct symbol, and if the measurements were spaced according to the time intervals for that section (i.e., Are fetal heart rate

measurements spaced half-an-hour apart? Are cervical dilation measurements spaced four hours apart?) Each worksheet was given an overall score, which included the scores for both case studies, and each case study score was evaluated separately.

4.2.2 Results

Scores were calculated as a percentage of total points correct out of the total possible points. An unpaired t-test was performed to identify differences between groups, particularly if Groups 2 and 3 showed any improvement in performance over Group 1, the control group. There was not a significant difference in the scores for Group 1 (M=.582, SD=.183) and Group 2 (M=.632, SD=.101); $t(25)=0.880$, $p=0.388$. There was also not a significant difference between Group 1 and Group 3 (M=.655, SD=.142); $t(23)=0.472$, $p=0.641$. These data are recorded in Table 3.

Group # and PartoPen Mode	**Avg. Score**
Group 1 – silent logging mode	58%
Group 2 – use mode, no training	63%
Group 3 – use mode, training	66%

Table 3. Average scores on worksheet completion task divided by PartoPen functionality group number. This table illustrates an increase in student performance with increasing PartoPen functionality and training.

The average scores for each group based on patient case study data are shown in Table 4. Using an unpaired t-test, the difference between Group 1 (M=.520, SD=.141) and Group 3 (M=.722, SD=.089) for the patient case study Mrs. C, a prolonged labor resulting in a CS, was found to be significant; $t(8)=2.709$, $p=0.0267$. These data suggest that for more challenging or complex labor cases, the availability and utilization of the PartoPen instruction prompts promotes more accurate form completion.

	Normal Labor	Prolonged SVD	Prolonged CS
Group 1	61.3%	58.6%	**52.0%**
Group 2	63.5%	62.9%	62.9%
Group 3	65.2%	62.7%	**72.2%**

Table 4. Average scores on worksheet completion task for fourth year students divided by patient case study and group number. This table illustrates a significant difference (p-value = .0267, between Groups 1 and 3 for a prolonged CS labor).

After each group completed the worksheet task, students were asked to participate in a short focus group session. The focus group discussion centered on how the partograph is currently taught and used, and the students' experiences using the PartoPen to complete the partograph. Currently, the partograph is covered only briefly in the nursing curriculum; practice and actual use occur during students' clinical rotations in the labor ward. The students were asked if there were particular parts of the partograph that were difficult to complete, or which were not adequately covered in class or during clinical rotations. Students unanimously reported that plotting contractions was one of the most difficult sections of the partograph, because both duration and frequency are plotted together using a combination of bar charts and coloring patterns. Students also reported unanimously that plotting descent of the fetal head was challenging. Difficulties plotting descent of the fetal head can also be attributed to having to plot on the same graph as another measurement (cervical dilation), but may also be due in part to the nursing school transitioning to a different partograph version that requires users to plot the descent in increments of one instead of two, and on the left side of the graph instead of the right.

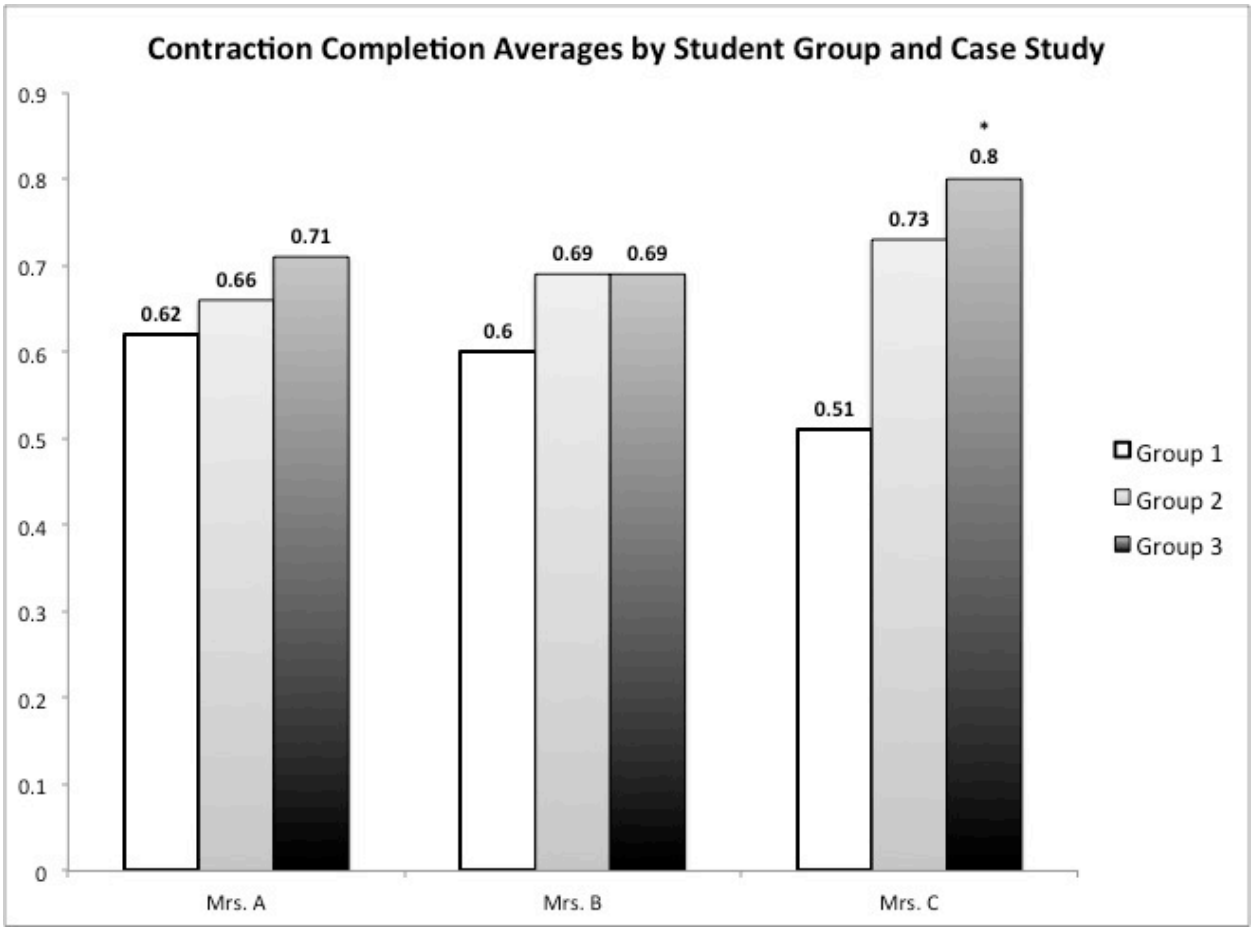


Figure 17. Partograph worksheet completion results for contractions organized by student group and by case study (Mrs. A: normal labor, Mrs. B: prolonged SVD, Mrs. C: prolonged CS). * = p < .05 using an unpaired t-test.

In Figure 17, the completion scores for plotting contractions for each group are shown. These data illustrate that improvements were made in all three case studies (Mrs. A, B, and C) between groups that did and did not use the PartoPen. There was a statistically significant improvement in contraction plotting on the Mrs. C case study between Group 1 (M=.513, SD, .232) and Group 3 (M=.803, SD=.139); t(8)=2.399, p=0.0433. In Figure 18, the student data for completing descent of the fetal head measurement is shown. For the descent measurements, there was significant improvement on the Mrs. C case study between Group 1 (M=.337, SD=.152) and Group 2 (M=.585, SD=.162); t(10)=2.699, p=0.0223. There was also a very significant

improvement on descent plotting on the Mrs. C case study between Group1 and Group 3 (M=.705, SD=.137); t(8)=4.028, p=0.0038. These results are consistent with the PartoPen functionality as audio from the pen is only triggered in cases where prolonged or obstructed labor occurs.

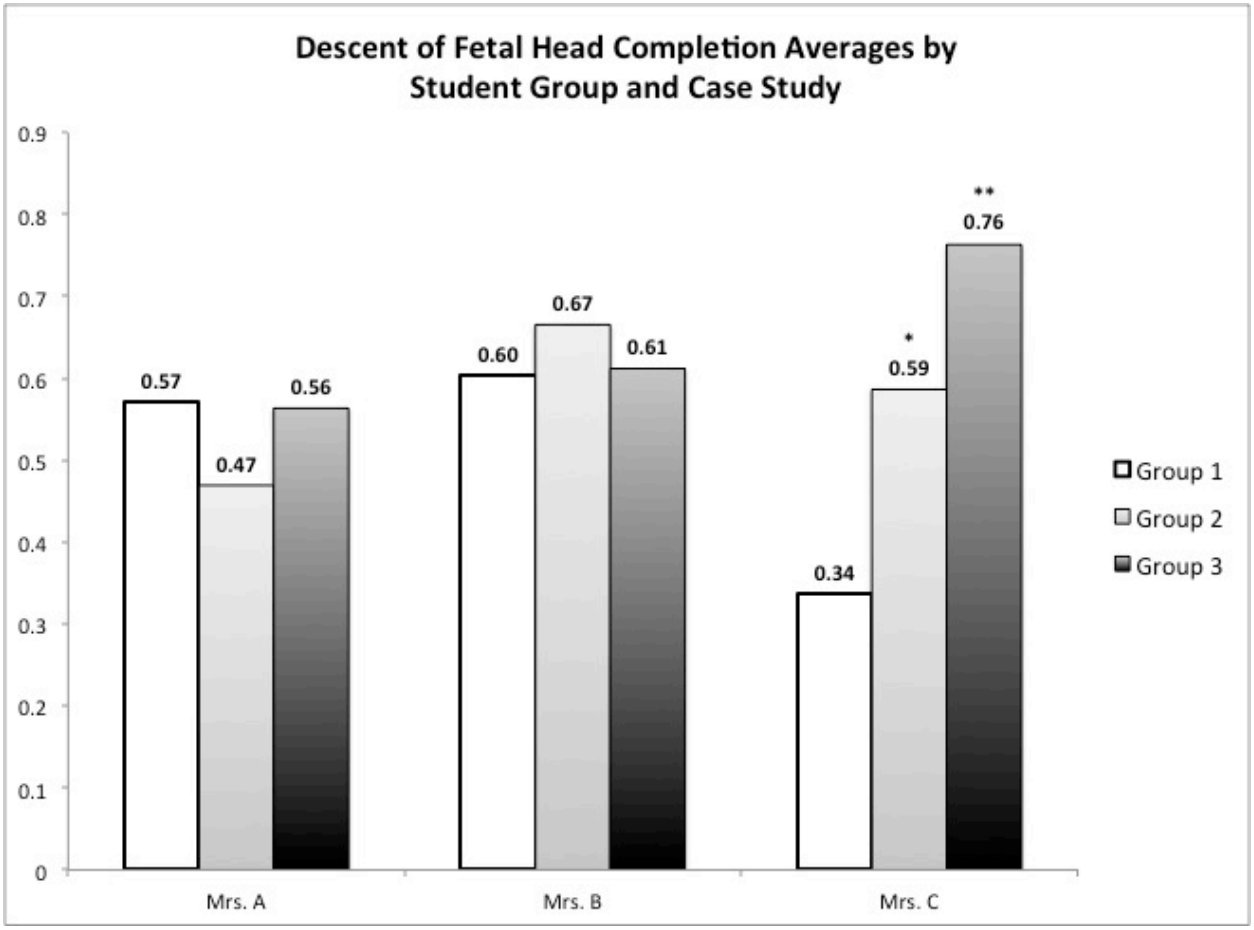


Figure 18. Partograph worksheet completion results for descent of the fetal head organized by student group and by case study (Mrs. A: normal labor, Mrs. B: prolonged SVD, Mrs. C: prolonged CS). * = p < .05 using an unpaired t-test, ** = p < .01 using an unpaired t-test.

The results from this study illustrate that using the PartoPen in classrooms can improve students' ability to correctly complete a partograph form, particularly for complex cases, and for the most challenging sections of the form. The study results also suggest that training on the PartoPen device does not significantly affect student performance on partograph completion

tasks. These results support the hypothesis that a significant increase in partograph completion and accuracy can be achieved with little or no training on the device itself largely due to the intuitive design, push-based functionality, and enhancement – rather than replacement – of the current paper-based system. Rural and traditional birth attendants are likely similar to nursing students in the amount of partograph training they have received, which motivates a continuation of the clinical study that attempts to identify where along the healthcare continuum the PartoPen system can provide the greatest benefit to healthcare providers and patients

4.3 July-August 2012 – Maternity Ward Study at KNH

The third PartoPen study took place at Kenyatta National Hospital. The primary goals of this study were to (1) evaluate the PartoPen for usability in labor wards; (2) determine if PartoPen use impacts partograph completion; and (3) examine the broader impacts of the PartoPen on patient care and maternal health outcomes. The focus of the maternity ward study was the evaluation of the PartoPen as a clinical decision support system (CDSS), and the testing of its more advanced features – reminders and reminder IDs – that were not active or necessary during the nursing student study. The work in this section will be presented as a full paper and published in the conference proceedings of the 2013 International Conference on Information and Communication Technologies for Development held in Cape Town, South Africa [19].

A previous systematic review [146] identified five key features of CDSSs that strongly correlated with improved patient outcomes:

1. automatic delivery of decision support
2. integrated rather than stand alone solutions
3. computer-generated decision support
4. systems that prompt physicians to record a reason for choosing alternate care

5. systems that provide a recommendation in addition to an assessment.

The PartoPen was designed to provide four of the five CDSS features identified in this review to assist nurses in providing quality, timely care to patients (1, 2, 3, and 5). The quantitative evaluation metric for the maternity ward study was partograph completion, as determined by an objective grading rubric that was created for that purpose. The system was also qualitatively evaluated using occupational observation and participant surveys.

4.3.1 Methodology

The maternity ward study was conducted in the labor ward at KNH. The study site characteristics were described previously in the usability study section (5.1.1) on page 92. The maternity ward study was designed as a pre- and post study, which compared partograph completion rates before and during the PartoPen intervention.

4.3.1.1 PartoPen Introduction to the Maternity Ward at KNH

There were three phases in the introduction of the PartoPen system at KNH: (1) training nurses how to use the PartoPen system, (2) introducing the PartoPen system for use during 2-3 shifts per day, and (3) establishing sustainable infrastructure and gradually reducing researcher support in the labor wards.

During the first phase, small groups of nurses received a 10-20 minute introduction to the project and were trained on how to effectively use the system during their shift. Nurses were given a demonstration of the PartoPen functionality to introduce them to features of the system (reminders, audio decision-support, and additional instruction access), as well as a brief tutorial on exchanging pens during shift changes. The first phase lasted one week, and each morning nurses were given the tutorial on how to use the PartoPen system. By doing this for one week, we were able to train almost all of the nurses who would be using the pens during the study.

In phase two, researchers introduced the PartoPen system in the KNH labor wards during the day shifts – approximately 7:30AM until 6:00PM. During the introduction week, the PartoPen functionality and the study design were adjusted to fit various environmental factors that had previously been unknown, such as modifying reminder sounds and text wording to account for noisy and busy environments, and simplifying the patient reminder ID system to allow nurses to create short, personalized identifiers for patients, rather than relying on the handwriting recognition in the pen to capture the patient's full name.

During the third phase, no changes were made to the code or the study design in order to keep study conditions consistent for data collection purposes. Quantitative data was collected using the PartoPen desktop logging application and the Livescribe Desktop application; these data were downloaded every day at the beginning of the morning shift. Data downloaded to the PartoPen logging application included the following time-stamped variables: when audio prompts were played, which audio prompts were played when measurements were made, how many times instruction buttons were tapped, when the partograph form was started and completed, and which pen completed the form. The Livescribe Desktop application captured and stored PDF copies of the completed partograph forms from the PartoPens. Qualitative observations were also recorded during the PartoPen study. On completion of the study, nurses were asked to complete a survey on their experience before and during the PartoPen project.

4.3.1.2 Partograph Collection Before and During the PartoPen Study

In order to evaluate baseline partograph completion rates at KNH before the PartoPen study, a Kenyan research assistant scanned the 352 partograph forms completed in the month prior to PartoPen introduction (June 2012). These partographs were compared to the 397

partograph forms (also scanned by the research assistant) that were completed during the one-month PartoPen study (August 2012).

All of the partographs collected during the pilot study were first categorized by delivery mechanism – spontaneous vaginal delivery (SVD) and cesarean section (CS). The CS deliveries were further categorized into emergency CS (EmCS) and "other", which included voluntary CS and CS due to previous CS scars. Deliveries of twins, triplets, or deliveries lasting less than one hour were noted among the SVD partographs, but not included in the initial data analysis because the partograph a) is not designed to monitor multiple births, and b) does not provide beneficial monitoring for labors that are less than one hour.

Of the 352 patient files collected in June, 155 were duplicates, did not contain a partograph, had a blank partograph, the patient arrived in the second stage of labor, or the patient underwent a planned cesarean section. When a woman arrives in the second stage of labor, she usually gives birth shortly after arriving at the hospital, thus not warranting the use of an ongoing monitoring tool like the partograph. Similarly, women coming to the hospital to receive a scheduled cesarean section are not monitored using the partograph because they are often not yet in labor. Of the 397 patient files collected in August, 206 of them fell into one of the no-partograph categories listed above. The remaining patient files – 191 for August and 194 for June – were separated into spontaneous vaginal deliveries (SVD), cesarean sections (CS) that were not scheduled or elective, and intrauterine fetal deaths (IUFD). In August, there were 151 SVDs, 30 CSs, and 10 IUFDs. In June, there were 153 SVDs, 31 CSs, and 10 IUFDs.

The collected partographs were graded and checked by two pairs of research assistants according to the evaluation rubric described in Section 4.3.1.3 on page 109. Each partograph received two scores: a composite completion score and a summary score. The composite score

was calculated by dividing the number of points received by the total number of points possible for all three grading criteria (mark presence, correct mark symbol, and correct mark spacing) and for each partograph section (fetal heart rate, cervical dilation, etc.). The summary score reflects the completion percentage for the partograph summary section at the bottom of the form, which summarizes the labor, and is usually completed after a patient delivers.

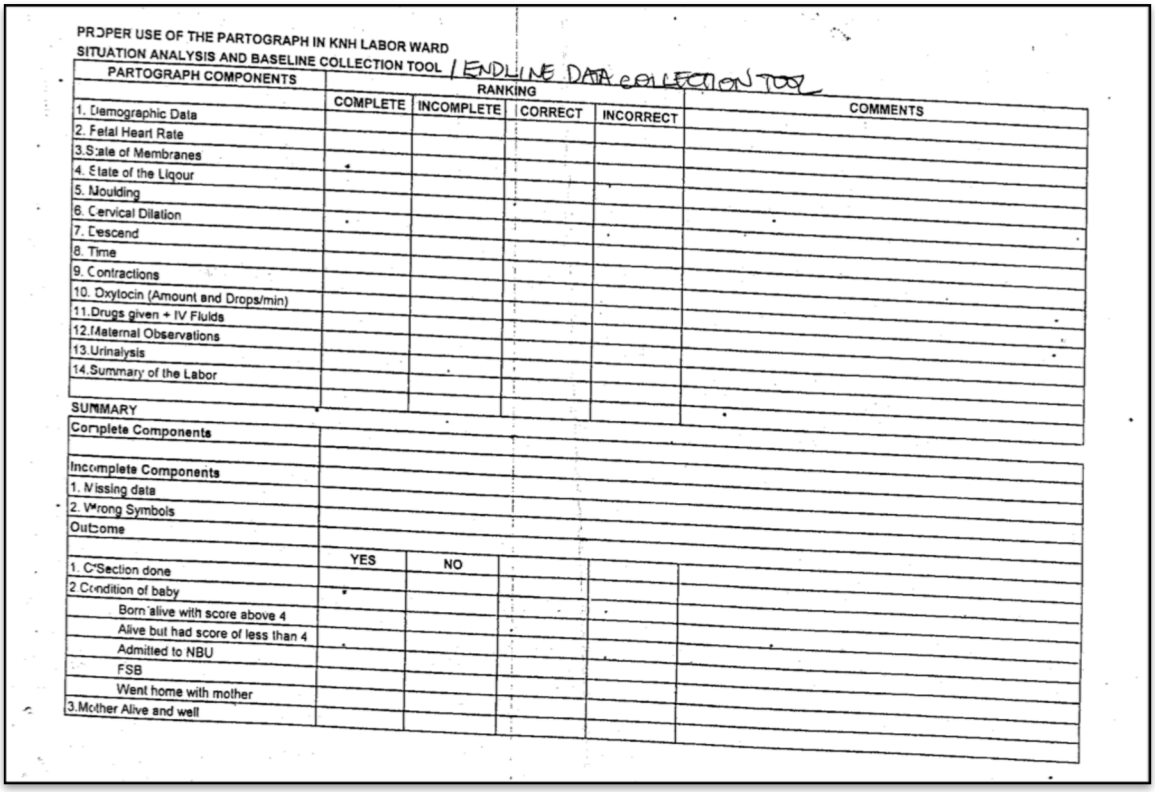
4.3.1.3 Partograph Evaluation and Grading Rubric

Partograph "completion" was measured using a partograph completion rubric, similar to the rubric used in the nursing student study. According to this rubric, a complete partograph has measurements for all of the partograph form sections, and a complete labor summary. The rubrics used in both the nursing student and maternity ward studies are loosely based on the rubric used internally by KNH staff for hospital administrative purposes. Unlike the nursing student study where the number of expected measurements was known, the rubric for the maternity ward study used a patient's time of admission and time of delivery to calculate the expected number of measurements on the partograph form.

Previous partograph studies [3], [7], [8], [16], [137], [138] that consider completion rates, data quality, and outcomes, did not fully describe the procedures used to quantitatively evaluate partograph completion, or they use varying degrees of subjective evaluation to determine partograph completeness.

At KNH, partographs are evaluated using a rubric that has "complete" and "incomplete", "correct" and "incorrect" boxes for each partograph category – fetal heart rate, molding, cervical dilation, etc. For each partograph category, the partograph being evaluated is marked as either complete or incomplete, and correct or incorrect (see Figure 19). Due to the wide range of variation in how partographs are used and completed, this basic evaluation rubric does not

capture either actual partograph completion, or the actual usefulness of the data recorded on the partograph.



PROPER USE OF THE PARTOGRAPH IN KNH LABOR WARD
SITUATION ANALYSIS AND BASELINE COLLECTION TOOL / ENDLINE DATA COLLECTION TOOL

PARTOGRAPH COMPONENTS	RANKING				
	COMPLETE	INCOMPLETE	CORRECT	INCORRECT	COMMENTS
1. Demographic Data					
2. Fetal Heart Rate					
3. State of Membranes					
4. State of the Liqour					
5. Moulding					
6. Cervical Dilation					
7. Descend					
8. Time					
9. Contractions					
10. Oxytocin (Amount and Drops/min)					
11. Drugs given + IV Fluids					
12. Maternal Observations					
13. Urinalysis					
14. Summary of the Labor					
SUMMARY					
Complete Components					
Incomplete Components					
1. Missing data					
2. Wrong Symbols					
Outcome					
	YES	NO			
1. C'Section done					
2 Condition of baby					
Born alive with score above 4					
Alive but had score of less than 4					
Admitted to NBU					
FSB					
Went home with mother					
3. Mother Alive and well					

Figure 19: The partograph grading rubric used at KNH for internal record keeping.

After the initial data collection phase, we began developing an objective evaluation rubric for measuring partograph completeness. This rubric has grading criteria for each partograph category, including a separate set of grading criteria for the labor summary printed at the bottom of each partograph. For each partograph category, there are three grading criteria: measurements recorded, symbols correct, and spacing correct. The total possible number of points for each of these grading criteria is determined by the admission time and delivery time of the patient. For example, if a patient is admitted at 1:00 PM, and delivers at 4:00 PM, there would be seven possible points for each of the half-hour measurements (fetal heart rate, pulse, contractions, etc.), plus two possible points for each four-hour measurement (cervical dilation, descent of the fetal

head, etc.) Fetal heart rate would then be evaluated on "measurements recorded" out of seven points, such that if the nurse plotted seven marks on the fetal heart rate portion of the partograph, 100% completion for measurements recorded would be achieved. For fetal heart rate, the partograph would also be evaluated for correct symbols (i.e., a solid dot with connecting lines between each dot/measurement) and correct spacing (i.e., one box between each measurement), which would be evaluated out of six points as there are only six spaces between seven possible measurements.

One of the potential drawbacks of this evaluation rubric is that equal weight is given to each of the partograph categories. In reality, there are several partograph measurements that should be weighted more heavily to reflect their level of importance in the labor monitoring process. A 2010 study by Qureshi et al. [7], found that contractions, cervical dilation, descent of the fetal head, and fetal heart rate are four of the most important measurements recorded on the partograph. In addition, widespread lack of equipment and resources (such as urine analysis strips and blood pressure cuffs) was reported as a common factor leading to incomplete partograph records.

4.3.2 Results

The results of the maternity ward study include quantitative results from the evaluation and scoring of the paper partograph forms collected for June 2012 and August 2012, and qualitative results from the post-study surveys and researcher observations. The quantitative results in this section reflect a first and second analysis of the collected data. A third analysis of the data collected during the maternity ward study, motivated by the follow-up study conducted in June 2013, is described in Section 4.4 on page 120.

4.3.2.1 First Quantitative Partograph Completion Comparison

Figure 20 depicts the average summary completion scores for each birth outcome, illustrating a significant improvement for CS cases, and general improvements across the board. Figure 21 depicts the average composite scores for each birth outcome (SVD, CS, and IUFD). The average composite scores for June and August are approximately the same for all three categories.

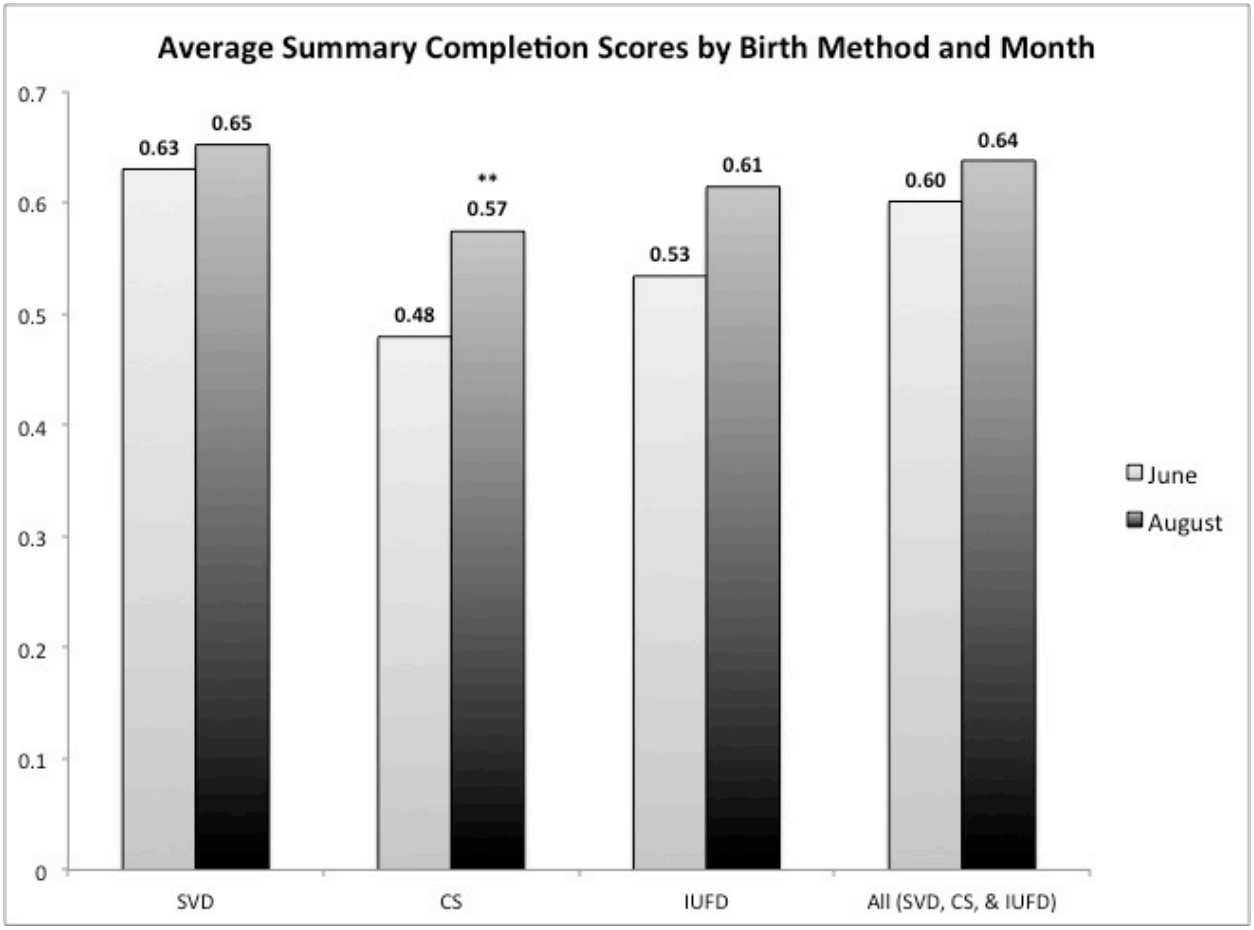


Figure 20. Average partograph completion scores for the summary section of the form by spontaneous vaginal delivery (SVD), cesarean section (CS), and intrauterine fetal death (IUFD). Improved completion rates occurred for all birth method categories, with a significant difference occurring for CS cases.

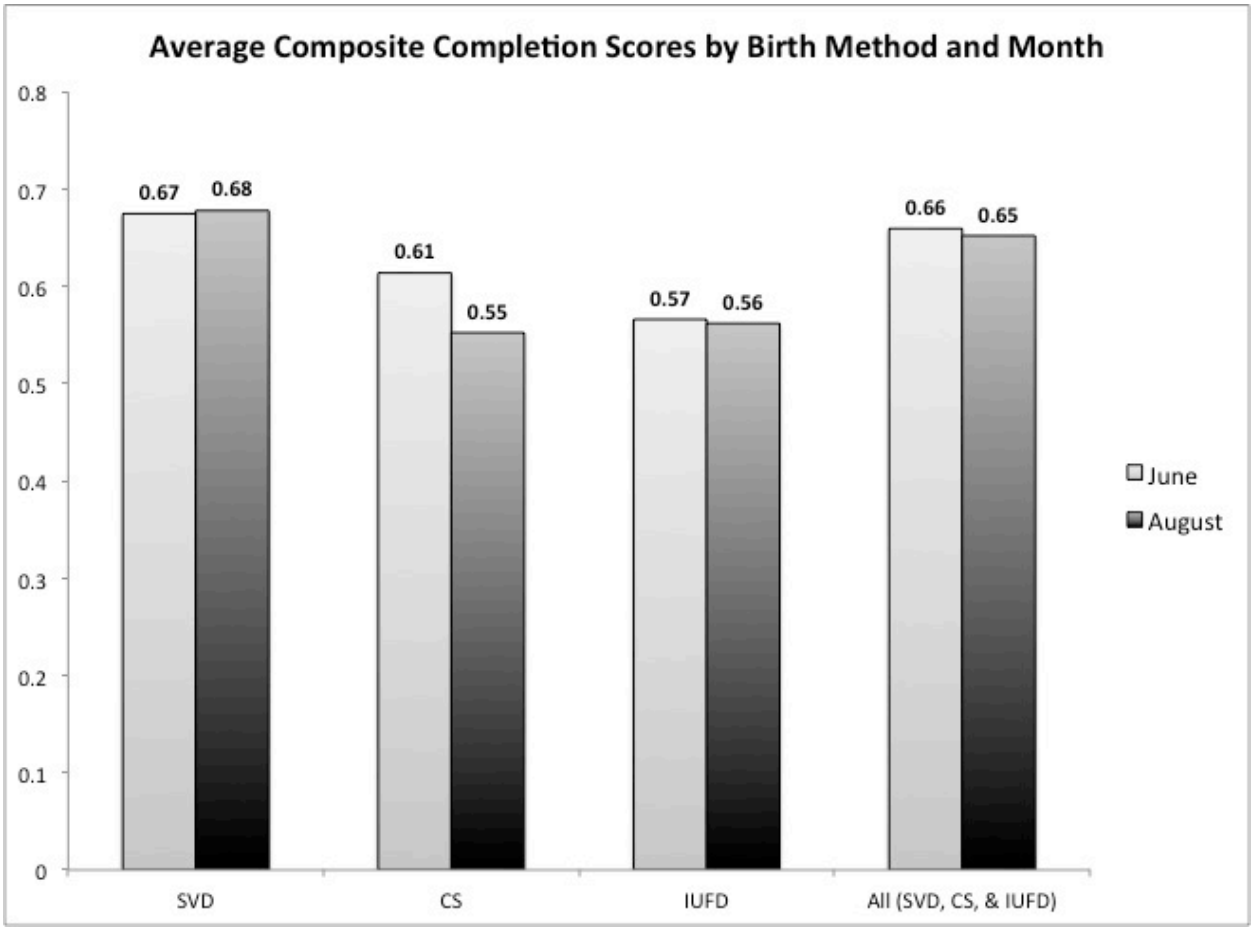


Figure 21. Average partograph completion scores for the graphical sections of the form by spontaneous vaginal delivery (SVD), cesarean section (CS), and intrauterine fetal death (IUFD). No significant differences were found for any birth method category.

The improvement in completion scores for the summary section of the partograph can be attributed to several possible factors. First, the partographs used in June were slanted and blurred due to frequent photocopying, whereas the partographs used in August were each printed individually (to assure the unique dot pattern on each form). This made the August partographs significantly easier to read and complete. Second, the improvement in summary scores is likely a result of the increased awareness and underscored importance of the partograph that occurred during the PartoPen study. The lack of improvement in completion rates for the composite partograph scores as a result of the increased focus on the partograph is likely due to the effects

of understaffing. Understaffing thwarts completing the graphical portion of the partograph because the ratio of nurses to patients (often between 1:5 and 1:10) does not allow for regular half-hour measurements to be taken for each patient. The PartoPen system cannot replace trained staff members, and does not directly address the understaffing barrier facing partograph completion. The nurses' self-reported improvements in partograph completion rates may be explained by the higher completion percentages for the summary section of the partograph despite little improvement in the completion of the graphical portion of the partograph. In order to approximate the difference in clinical decision support effectiveness between the "built-in" alert and action lines on the partograph, and the added audio decision support for the PartoPen corresponding to these lines, the partographs were examined to see how many crossed the action line. Figure 22 depicts the percentages of partographs with a cervical dilation measurement plotted across the action line for SVDs and CSs for both June and August. The number of SVDs that crossed the action line went down from roughly 8% in June to 4.6% in August. These data suggest that more patients in June had partographs indicating potential obstructed or prolonged labor that may not have been acted upon. The decrease in SVD cases crossing the action line in August is a plausible indicator that decision making improved in August, with more potential obstructed labor cases being addressed before the action line was crossed. Labors crossing the alert line in August may have been addressed with oxytocin augmentation and artificial rupture of the membranes – two recommendations emitted by the PartoPen when the alert line is crossed. These actions may have accelerated and strengthened the labors, which might have otherwise been prolonged if left unaddressed.

The number of CSs that crossed the action line went up from 29% in June to 33% in August, which suggests that more of the CSs in August had a partograph that recommended a

cesarean section as one possible course of action. These results may indicate that fewer unnecessary C-sections were performed in August, possibly as a result of more complete and accurate labor monitoring documentation.

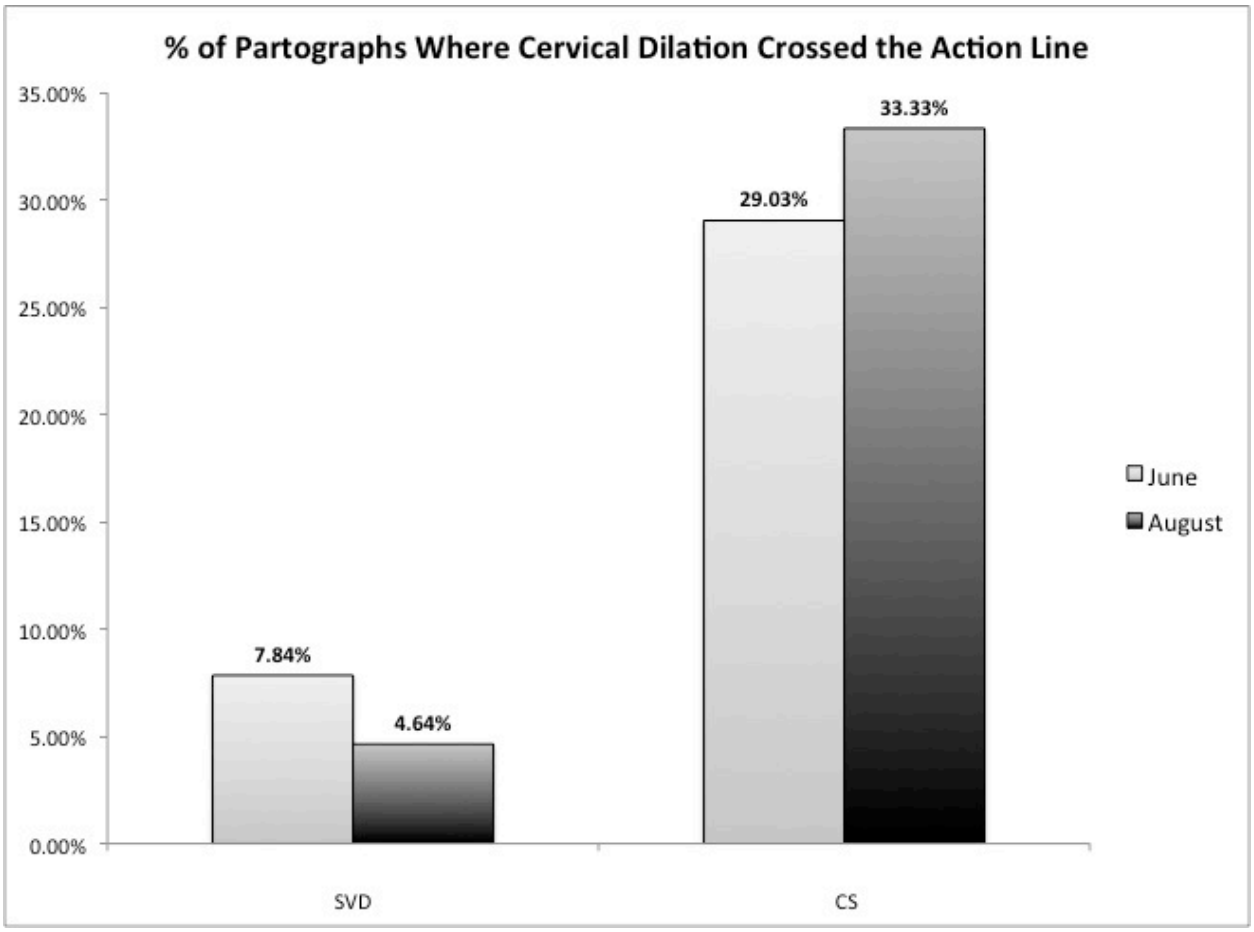


Figure 22. Percentage of partographs that had a cervical dilation measurement plotted across the action line by spontaneous vaginal delivery (SVD) and cesarean section (CS). There were fewer SVD cases with a measurement across the action line in August, and more CS cases with a measurement across the action line in August.

4.3.2.1 Second Quantitative Partograph Completion Comparison

After the initial broad data analysis, a more fine-grained analysis was performed on the PartoPen data to ascertain if and how the PartoPen functionality impacted partograph completion rates. Partographs completed in June were compared to August partographs that were actually completed with the PartoPen. The PartoPen was used to complete 48 such forms. PartoPens were

only given to nurses at KNH during the study, excluding the nursing students who were actively working in the labor ward as part of their clinical rotation. Student-completed partographs in August, which were not completed with a PartoPen, were excluded from this analysis. In addition, many partographs were only partially completed with the PartoPen, due to nurse rotations and patient handoffs. These partially completed partographs were also excluded from the second analysis.

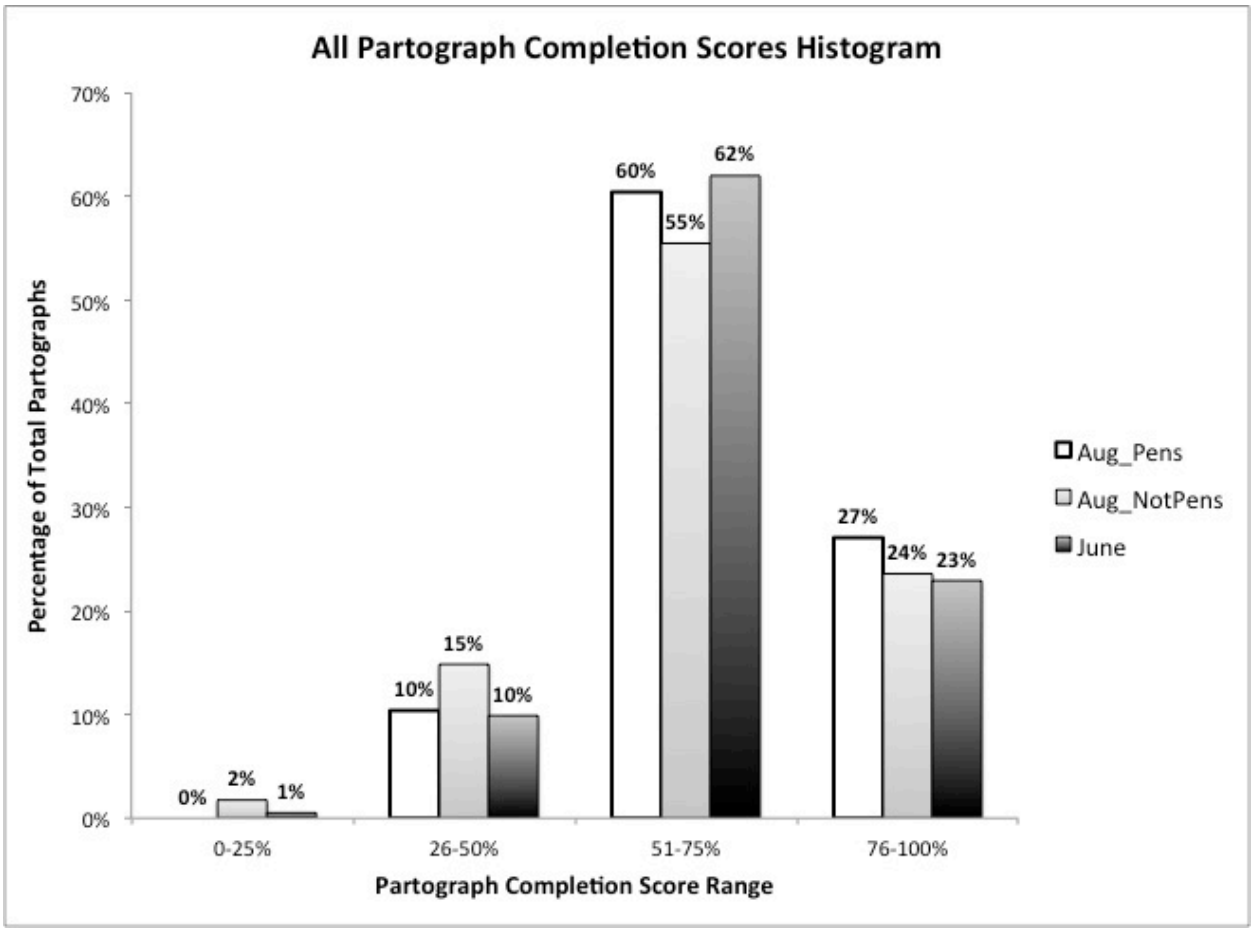


Figure 23: A histogram of partograph completion scores for August partographs completed with a PartoPen, August partographs not completed with a PartoPen, and June partographs.

The comparison of all the partographs completed with PartoPens versus the August partographs not completed with the PartoPens versus all of the June partographs is represented in

Figure 23. This histogram illustrates that August partographs completed with the PartoPens never received a completion score lower that 25%, whereas both June and August partographs completed without the PartoPen did. Additionally, the August partographs completed with the PartoPen had the highest percentage of partographs in the 75-100% completion range.

4.3.2.3 Qualitative Analysis of KNH Post-Use Surveys and Interviews

After three weeks using the PartoPen system consistently on every shift, nurses were asked to fill out a short survey that captured demographic information about the participant, and gathered before-and-after information about PartoPen use. The survey consisted of eight Likert scale questions, and six free-form response questions.

On average, nurses self-reported an improvement of +2, on a scale of 1 to 10, in partograph expertise during the PartoPen project, a 9 out of 10 for usability of the PartoPen, and a 9.2 out of 10 for usefulness. Nurses also reported that the number of partographs they completed during the PartoPen study was, on average, 25% more than they completed before the study. This increase in partograph completion rates is supported by initial data analysis on the partograph forms, and by an internal report by the hospital administration. In addition to the functionality provided by the PartoPen, which encouraged higher rates of partograph completion, the general increase in conversation and interest in the partograph due to the PartoPen study was also a likely contributing factor to the improved partograph completion rates.

Overall, the quantitative data gathered from the surveys suggest an increase in partograph knowledge among nurses, an increase in the number of partographs completed, and strongly positive perceptions of the PartoPen's usability and usefulness.

4.3.2.4 Data Analysis Implications for Patient Referral

The issue of patient referral from surrounding district hospitals and health centers was frequently mentioned among the nurses and doctors at KNH. Patients often arrive at KNH past the point of effective care due to the many delays in seeking, reaching, and receiving quality care. This issue, combined with serious understaffing and resource shortages, is one of the key areas of future work for the PartoPen project.

Of the IUFD cases collected in August, 30% were referral patients. In June, 20% of the IUFD cases were referred from other hospitals. Of the CS cases collected August, 10% were referral patients. In June, 13% of the emergency CS cases were from referral patients. Only 3% of SVD cases in both June and August were from patients who had been referred from other hospitals.

These data illustrate that the majority of complicated and high-risk cases that occur at KNH are from patients who are referred from other hospitals. The low completion rates for both CS and IUFD partographs underscore the challenge of attending to high-risk patients that arrive without appropriate documentation or any record of labor history from the referring hospital. The time needed to perform a comprehensive intake exam on a referred patient could be reduced if the patient arrived with a completed partograph illustrating the progress (or lack of progress) of the labor, as well as the complications that led to the patient's referral. This time could potentially be reduced further if data were transferred to the receiving facility before the patient arrived. The PartoPen system, if implemented at district level hospitals and health centers – the primary referring facilities to hospitals like KNH – could transmit partograph data to the receiving facility before the patient arrives, giving nurses, doctors, and surgeons adequate time to review patient information and prepare.

4.3.3 Preliminary Discussion of Results

The preliminary data analysis of the maternity ward study data exhibited no statistically significant improvements to partograph completion rates during the PartoPen deployment at KNH. These results can be explained by a number of possible factors. First, the small improvements that were observed are most likely attributable to the increased focus and discussion about the partograph during the study. In addition, the printed forms were easier to read and complete than the blurry photocopied versions that had been in use, which was cited by several of the nurses as a positive outcome of the study. Second, the rubric used to evaluate "completion" went through several iterations, and continues to be improved and refined by project researchers and our medical partners. While all of the data was graded using the most recent version of the rubric, a comprehensive standard for evaluating partograph completeness has yet to be adopted. Third, nurses at KNH are among the best-trained nurses in Kenya. The minimum-viable-product model of the PartoPen software that was deployed at KNH to test the concept did not provide the depth and breadth of functionality that would have been necessary to move the needle for these highly skilled nurses. However, it is encouraging that despite the introduction of a new technology, and the implementation of a month-long study, the partograph completion results according to the rubric remained relatively unchanged.

The positive perceptions of the PartoPen system, and enthusiasm for continued use by nurses and hospital administration motivated a continued deployment in the maternity ward at KNH. At the conclusion of the maternity ward study, 20 PartoPens were given to KNH for continued use in the labor ward. The printer, a three-month supply of paper and toner, and ink and cap replacements for the PartoPens were also donated to support ongoing use of the system

after the August 2012 study. Nine months after the completion of the maternity ward study, a follow up study was conducted. The results of this study are described in the next section.

4.4 June 2013 – KNH Follow-up Study

In June 2013, a follow-up study was conducted in the KNH maternity ward to review the PartoPen deployment that had been in use for nine months. The three goals for this visit were (1) to conduct a paper survey with KNH nurses on the impact of the PartoPen since implementation; (2) to conduct a computerized survey with KNH nurses to evaluate partograph forms and validate the grading rubric used during the studies in 2012; and (3) to evaluate the PartoPens and the associated printing equipment with respect to technology-related problems or concerns.

Upon returning to the KNH labor ward, we found that all 20 of the PartoPens were accounted for, 19 out of the 20 PartoPen were functional, and over 600 digital partograph records were present on the PartoPens, collected from September 2012 to April of 2013 (the printer used to print dot-patterned partographs failed in April 2013, and replacement parts were not readily available in Nairobi).

4.4.1 Paper Surveys

Thirteen of the 26 nurses who completed the survey self-reported that they were 'experts' using the PartoPen system. The majority of the nurses (19 out of 26) used some combination of partograph information and other patient information to make decisions about patient care. The nurses were asked to rank in order of importance the different sections of the partograph as they relate to providing quality patient care. Nine nurses ranked patient name and age as the most important section of the partograph to complete. Eight nurses ranked fetal heart rate as the most important section of the partograph, and seven nurses ranked the partograph sections sequentially (i.e., the most important section is the topmost section of the form, and the

least important is the bottommost portion of the form). One nurse ranked contraction frequency as the most important, and one nurse ranked cervical dilation as the most important section of the partograph to complete. The responses from the survey suggest that certain information on the partograph is more useful for making critical decisions about patient care, which may indicate that a simplified and restructured form that highlights these sections (and makes them easier to complete) could be useful in this setting. Nurses largely prioritized patient information and fetal heart rate as the most important portions of the form. In the PartoPen study, some of the qualitative feedback received by nurses indicated that using larger boxes for information entry for these sections considerably improved the usability and readability of these critical pieces of information.

The survey also asked nurses to identify if there were certain kinds of labor or patients who do not need a partograph. Twenty of the 26 nurses said that there were patients who do not need a partograph during labor. Elective cesarean sections, false labors, and patients who arrive already in the second stage of labor were the most common responses for labors that do not require a partograph to monitor labor progress. Elective cesarean sections are scheduled in advance and are categorized separately from emergency C-sections that happen as a result of complications during labor. Additionally, Kenyatta National Hospital, as the leading referral hospital, receives a very high volume of patients who are in the second stage of labor. Although KNH administrative policies require that a partograph be used during all labors without exception, staff shortages make prioritization necessary when deciding to begin or continue a partograph for a patient. Since KNH is a referral hospital, many patients arrive late in labor in poor condition, and completing paperwork or a partograph is not the highest priority of hospital staff. The result is blank or retroactively-completed partographs.

Nurses were also asked to identify patients and labor types that benefit the most from being monitored with a partograph. Nurses were allowed to circle more than one labor type out of SVD, CS, IUFD, Referral, and 'Other'. Twenty-three out of 26 nurses said that spontaneous vaginal deliveries (SVD), which are often categorized as 'normal' labors, benefit the most from correct partograph use. Eleven out of 26 nurses circled CS, emergency cesarean sections, as benefiting the most from partograph use, and 7 out of 26 nurses circled 'Referral'.

The survey asked several PartoPen-specific questions, including whether the nurses had observed any changes in the labor ward because of the PartoPen. This question was included in the survey to follow up on qualitative observations and discussions at the end of the 2012 studies that suggested labor ward nurses were feeling an increased sense of pride in their job because of the interest of senior hospital staff, and reliance on labor ward nurses to explain the project and demonstrate its functionality. Additionally, only labor ward nurses were given PartoPens, and this sense of privilege was mentioned several times by nurses as rewarding. Twenty-four of the 26 nurses said 'yes', there had been changes in the labor ward because of the PartoPen. The majority of the changes nurses described related to the reminder functionality of the PartoPen. Many nurses reported that the reminders were being effective for providing more timely care and making patient care more efficient. Better decisions and easier chart interpretation were also noted as significant changes resulting from PartoPen use in the labor ward.

4.4.1.1 Third Quantitative Partograph Completion Comparison

Based on these data, the data from the 2012 maternity ward study were re-examined, as follows. First, only the SVD partographs were included, as the majority of nurses indicated that SVD patients benefit most from partograph use. In addition, partograph sections that nurses

deemed most important (i.e., (patient information and fetal heart rate) were examined individually.

The SVD partographs were analyzed in three categories: August SVDs completed with the PartoPens, August SVDs completed without the PartoPens, and all of the SVDs from June. Using the same grading and evaluation rubric, these partographs were analyzed with respect to completion. The results of this analysis are shown in Figure 24. Frequency in this histogram is represented as a percentage of the total number of partographs present in the sample (37 August partographs completed with the PartoPens, 206 August partographs completed without the PartoPens, and 153 partographs completed in June). The histogram illustrates that August partographs completed with the PartoPens never received below 25% completion, and this set had the highest percentage of partographs in the 75-100% range.

The same set of SVD partographs was then examined, looking specifically at the completion of the 'patient information' and 'fetal heart rate' sections. While fetal heart rate completion did not change significantly between the three groups, a significant difference was observed in patient information completion between August PartoPen SVDs (M=.949, SD=.086) and June SVDs (M=.882, SD=.152) using a paired t-test ($t(188)=2.6178$, $p=.0096$). This difference may be attributable to several factors, including the improved readability and larger space for the patient information fields on the PartoPen version of the partograph form.

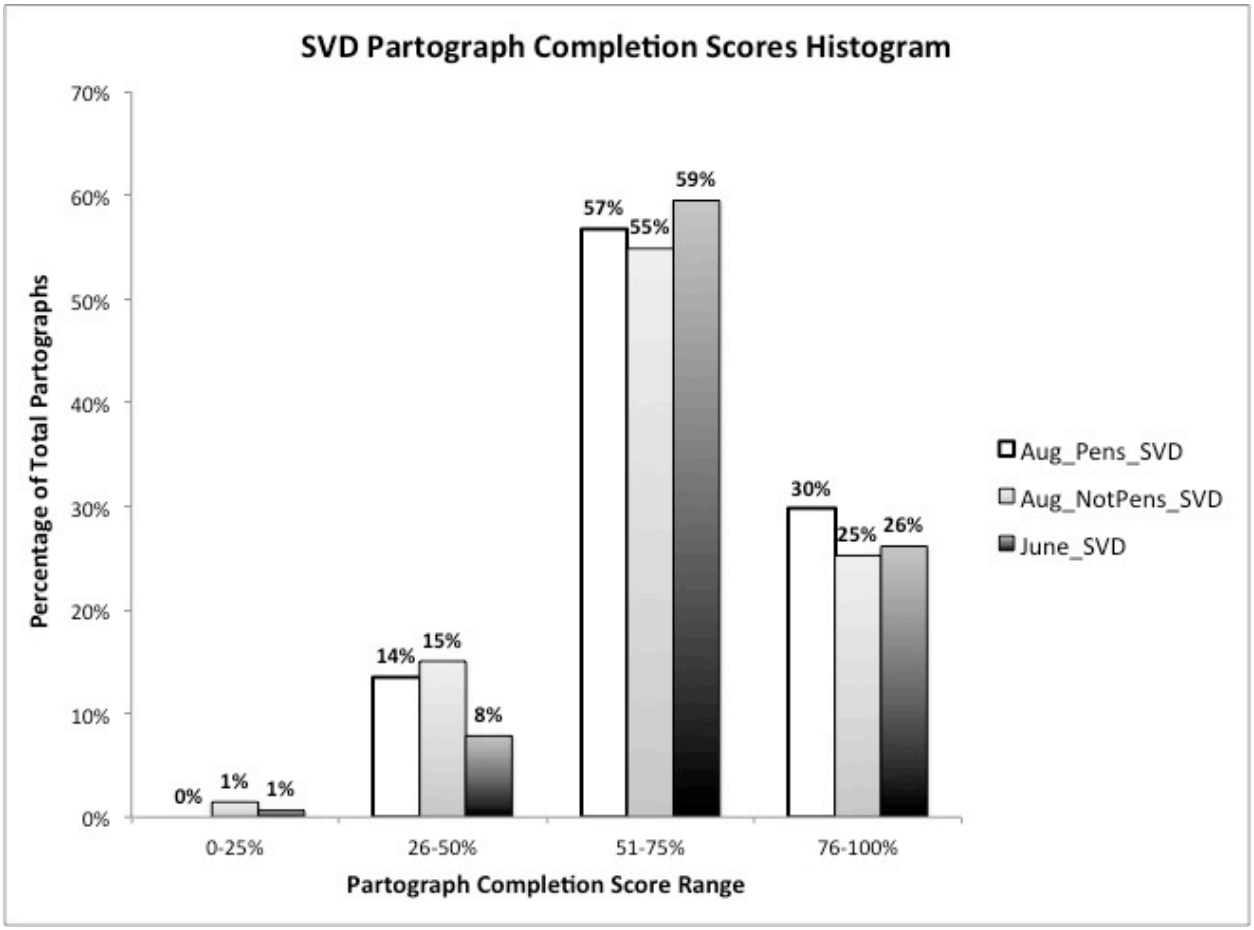


Figure 24: A histogram of SVD-only partograph completion scores.

4.4.3 Computer Survey

The computer survey was developed to test the PartoPen evaluation rubric used for generating partograph completion data in the PartoPen studies against nurses' perceptions of complete and useful partographs.

The computerized partograph survey was administered to seven nurse-midwives at Kenyatta National Hospital. The survey consisted of five anonymous partographs, which had been collected and scanned in August 2012 as part of the maternity ward PartoPen study. The partographs used in the survey were selected to capture various levels of "completeness," as represented by the scores derived from the PartoPen evaluation rubric, and delivery method (i.e., spontaneous vaginal delivery (partographs 1, 3, and 4) or cesarean section (partographs 2 and

5)). Partograph 4 was the most complete (96.08%), and Partograph 5 was the least complete (52.75%) when evaluated using the PartoPen evaluation rubric. The composite scores from the PartoPen rubric for Partographs 1-3 ranged between 67% and 85%. Each partograph was accompanied by five survey questions:

1) Is this partograph complete? Yes/No
2) Which sections are properly filled out? (Multiple selection from a list of all 19 partograph sections)
3) How useful is the information recorded on this partograph where 1 = not useful, and 5 = very useful? (Likert scale between 1 and 5)
4) Are you comfortable making decisions using only this partograph? Yes/No
5) If 'No', what partograph information would make you feel comfortable making a decision about this patient's care? (Multiple selection from a list of all 19 partograph sections)

Each nurse completed between 2 and 4 of the five possible partographs and associated survey questions, and were compensated with cellphone airtime minutes at the rate of 100 shillings per partograph completed. In total, four sets of responses for each of the five possible partographs were collected.

Table 5 illustrates the composite scores for each partograph as graded using the PartoPen evaluation rubric, and the average usefulness scores for each partograph as evaluated by nurses who participated in the survey.

The results in Table 5 illustrate that nurses' perceptions of the usefulness of a partograph align with the composite scores generated by the PartoPen evaluation rubric. Both the nurses usefulness scores and the composite scores for completion rank the partographs in the following

order from least useful/complete to most useful/complete: 5, 3, 2, 1, 4. The computer survey results suggest that (1) the PartoPen evaluation rubric produces good approximate measures of partograph usefulness, and (2) incomplete partographs are still deemed useful by nurses.

	Partograph 1	Partograph 2	Partograph 3	Partograph 4	Partograph 5
Composite Score (%)	84.31%	70.64%	67.94%	96.08%	52.75%
Usefulness Score	4.5	3.75	3	5	2

Table 5: A comparison of partograph composite scores from PartoPen grading and nurse perception scores for 'usefulness' for the same five partographs.

In addition, the results of the computer survey helped illustrate that lack of training is not a concern among nurses at KNH, as all the nurses were able to correctly identify what had and had not been filled out correctly (in accordance with the WHO manual on partograph completion). This finding significantly contributed to the conclusion that the PartoPen, designed for overcoming barriers to partograph use related to lack of training, was not likely to be as effective at KNH, because the primary obstacle to partograph completion at KNH (chronic understaffing) is not addressed by the PartoPen. Therefore, the PartoPen is likely to be more useful at a facility where lack of training presented a more significant obstacle to partograph form completion.

4.4.4 Evaluation of PartoPen Robustness

All 20 PartoPens that were left at KNH after the maternity ward study were present at the time of the follow-up study. Only one pen had failed (it would not turn on even when plugged in.) Damage to the pens was minimal, with small cracks in the plastic pen casing being the most pervasive non-critical issue. The mechanism for attaching the lanyard to the PartoPens was intact on 19 out of 20 of the pens, and replacement supplies (e.g., plastic o-rings and small key chains)

were still available. Many of the lanyards had some fraying, but were still usable. Only three pens were out of ink, and 19 out of 20 pens still had the black plastic caps attached.

A few pens had a sticky substance on them resembling blood. Although only 3 out of 20 pens displayed this characteristic, this is a concerning issue in a healthcare setting, especially in an environment where the prevalence of blood-borne pathogens is high. At KNH, nurses and doctors take the local prevalence of HIV very seriously, and there are many protocols in place to prevent exposure. The substance found on the pens was not definitively blood; however, the possibility of the pens being disease-carrying instruments is an important concern for future work. PartoPen cleaning and disinfecting protocols are currently being developed to address this concern.

The information from the KNH PartoPens was downloaded to the Livescribe Desktop (LD) software. Over 600 partographs were collected from the 20 pens dating from September 1, 2012 to May 5, 2013. The nurses and labor ward staff therefore, reliably used the system for nine months following the initial PartoPen study. The discontinuation in May was due to a printer issue (discussed in Section 3.9.3). The number of partographs collected from the pens does not reflect the total number of births occurring at KNH in the nine months between September and May, due to the high number of nursing student-facilitated deliveries (students were not given PartoPens during their labor ward rotations) and, as noted in the paper surveys completed by the nurses, there are patients who do not require a partograph (e.g., elective cesarean section patients.)

While the nine-month deployment of PartoPens at KNH was fairly successful in terms of robustness and durability, we wanted to test the limits of the PartoPen system. Three PartoPen research assistants simulated extreme conditions that might be found in a hospital or clinic

environment, and subjected the PartoPens to a battery of functionality tests under these conditions. The methodology and results of these tests are described in the following sections.

4.4.4.1 Pen Durability Testing Methodology

Twelve PartoPens were tested under experimental conditions designed to simulate situations that might arise in clinical settings and which would be expected to cause significant stress to the PartoPen. Before being subjected to experimental conditions, each pen was tested to ensure that the audio instructions, decision support and reminder features were functioning properly.

To test for audio instruction functionality, each instructional button on the partograph was tapped with the pen, and audio instructions were noted. Decision support functionality was tested by plotting three points in the fetal heart rate region of the partograph. One point was plotted above the line indicating 110 beats per minute, one was plotted on the line and another was plotted below the line. For the points plotted on or below the line indicating 110 beats per minute, audio and scrolling text decision support were expected. Additionally, three X's were plotted in the cervical dilation region of the partograph. One X was plotted to the left of the alert line, one between the alert and action lines, and one to the right of the action line. For the marks placed between the alert and action lines or to the right of the action line, audio and scrolling text decision support were expected. In order to test the reminder functionality, the pens were left on and audio reminders were noted after 30 minutes for each fetal heart rate point plotted and after 4 hours for each cervical dilation mark.

Before the stress tests were conducted, all twelve PartoPens were found to be fully functional, with the exception of the urine button. Due to an error in the audio file, none of the

PartoPens provided visual or audio instructions in response to tapping the urine button. This error was addressed in the PartoPen software following the stress tests.

Each pen was subjected to exactly one experimental condition. Before exposure to a test condition, each pen was turned on. After each pen was subjected to experimental conditions, the same operational tests were performed. Pen function was tested immediately following exposure to experimental conditions and re-tested one hour later. Test conditions included: submersion in simulated blood; submersion in hot water; submersion in room temperature water; cleaning the pen with alcohol, hydrogen peroxide, and bleach; stepping on the pen; dropping the pen onto concrete; burying the pen in the dirt; splattering with simulated blood; splattering with hot water; and splattering with room temperature water.

In a clinical setting, the PartoPen may come into contact with high volumes of blood. To simulate the consistency and color of blood, 1.5 cups of corn syrup were combined with 6 tablespoons of water and 12 drops of food coloring (10 drops of red and 2 drops of green coloring). The pen was submerged tip-down for 10 seconds and then submerged top-down for 10 seconds to ensure that each part of the pen was fully submerged for at least 10 seconds. The pen was removed from the simulated blood mixture and dried with a paper towel.

To test the effects of submersion in hot and room temperature water, one pen was submerged tip-down in one cup of 100^0C water and another pen was submerged in a cup of 20^0C water for 10 seconds. The pens were then flipped and submerged top-down for 10 seconds. The pens were removed from the water and dried with a paper towel before being tested.

The likelihood of pathogen exposure in a clinical setting would require the pens to be cleaned frequently. To test the effect of cleaning with alcohol (70% isopropyl alcohol), hydrogen peroxide, and bleach (6% sodium hypochlorite), 1 tablespoon of each cleaning solution was

absorbed into a separate paper towel. Three different pens were scrubbed vigorously for 20 seconds with a paper towel containing one of the three cleaning solutions. Every surface was scrubbed including the camera, speaker, screen, and charging adapter.

In a busy environment such as a hospital, it is possible that then pen will be dropped or stepped on. To test the effect of stepping on a pen, a pen was placed on a concrete floor and 120 pounds of continuous pressure was applied. To test the effects of dropping the PartoPen, a pen was dropped onto the concrete floor from a height of two meters. Dropping the pen was found to have a significant effect on the functionality of the PartoPen, which may be attributed to the height from which the pen was dropped and the angle at which the pen hit the concrete, which caused substantial damage to the camera located at the tip of the pen. The camera in the tip of the pen is required to produce any PartoPen functionality, as this is the device that reads the microdot pattern on the paper. Thus, any damage to the pen's camera will render the PartoPen functionality inert. If the pen had been dropped from a lower height or struck the concrete at a different point on the body of the pen, the damage may have been less significant.

If the PartoPen is used heavily for an extended period of time, debris may accumulate on the pen. To simulate the accumulation of dirt and debris on the PartoPen, a pen was buried under one inch of dirt and removed after 20 seconds. The pen was not cleaned before its functionality was tested.

To test the effect of blood splattering on the PartoPen, a half-teaspoon of the simulated blood mixture was drizzled on the front side of the pen and another half-teaspoon was drizzled on the back. The pen was then wiped clean with a paper towel before being tested.

The effect of spilling water at different temperatures on the PartoPen was tested by spilling one cup of 100^0C water on one pen and one cup of 20^0C water on another pen and

leaving the pens lying flat in the water for 5 seconds. The pens were then dried with a paper towel before being tested.

4.4.4.2 Pen Durability Testing Results

Five of the twelve experimental conditions (cleaning the pens with 70 percent isopropyl rubbing alcohol, bleach, and hydrogen peroxide, stepping on the pen and covering it in dirt) did not affect PartoPen functionality either immediately after exposure, or one hour after exposure.

The seven remaining tests of potential clinical scenarios had varying effects on the functionality of the PartoPen. Immediately after the pen was submerged in 100 degrees Celsius water the screen turned off and on and the pen failed all functionality tests. Some water was observed to penetrate into the screen. Following one hour, the screen turned on and the pen wrote, but no instructional buttons, visual or audio based decision support, or half hour reminders for fetal heart rate, contractions, and pulse measurements functioned. However, the pen was still recognized by the computer and capable of charging. Immediately after splattering a new PartoPen with hot water the screen and decision support of scrolling information functioned but the audio instructions did not. Thus, visual but not audio functions remained. Following one hour, the audio instruction functionality returned but was stuttering and hard to comprehend. The pen responded to all buttons, half-hour reminders continued and the computer recognized the pen.

The same tests were repeated on two more PartoPens with water at room temperature. Immediately after the pen was submerged in room temperature water it lost all functionality, with the exception of writing. There was no change to this loss of functionality after one hour passed. However, after three hours, the computer recognized the pen and one instructional button functioned. Following 30 more minutes, three and a half hours after initial experimental

exposure, a fetal heart rate reminder was correctly given. A new PartoPen was then splattered with room temperature water. Immediately after, all of the buttons functioned until the contractions section of the partograph. Following this section no instructional audio or visual scrolling decision support remained, however, the screen stayed on and the pen continued to write. Following one hour, all functionality was restored, including all half-hour reminders.

Following the experiments with water, the same scenarios were recreated with an artificial blood mixture. Immediately after submersion in the blood mixture the pen lost all functionality with exception of the screen staying on and its ability to write. One hour after experimental exposure all functionality returned with the exception of the half-hour reminders. However, around an hour and half after initial submersion the PartoPen began continuously restarting and thus became non-functional. The pen was still recognized by the computer. A new PartoPen was then splattered with the blood mixture. Immediately following exposure all of the buttons worked, however no audio or visually scrolling instructions were available when plotting fetal heart rate and cervical dilation. Following one hour all instructional buttons were recognized by the pen, however, the scrolling visual and audio decision support functions did not return.

The final scenario involved dropping the pen from a height of 2 meters onto a cement floor. Immediately following the drop, the screen remained on and the functionality was unaffected. However, very soon after, the instructional buttons, audio and visual decision support lost all functionality. Following one hour, the functionality of cervical descent and pulse returned and other instructional buttons functioned intermittently. The visual and audio decision support functions returned partially (the visual scroll and audio decision support worked on the line for fetal heart rate). The alerts and visual scroll functions below the line were delayed, and

alerts and scroll did not work for cervical measurements. The half-hour alerts continued, and the computer recognized the pen.

4.4.4.3 Summary

Livescribe digital pens are designed for use in home and office, not hospitals. For sustained clinical use, pens would need to be redesigned to provide better protection from fluid entry. Nevertheless, only one PartoPen in 20 failed over 9 months of actual clinical use. Even under simulated extreme conditions, the PartoPens were remarkably robust. The critical component of the PartoPen appears to be the camera in the tip of the pen, which captures the microdot pattern. If the camera is damaged, the PartoPen will not function. The PartoPens deployed at KNH illustrate that the PartoPen hardware and software can withstand the harsh environment of a busy hospital, and the lab tests illustrate the robustness of digital pens even under simulated extreme conditions. The results of the hospital deployment and the lab tests suggest that digital pens provide a relatively low-cost, reasonably durable solution that can be deployed in a variety of resource-constrained or harsh environments. Additionally, a critically important property of the PartoPen is that, even in the event of complete software failure, the PartoPen can still be used as a pen to record vital information on paper. Based upon disassembly and inspection of the LS pen used for the PartoPen, sealing the internal circuitry from fluids would be relatively straightforward.

4.5 Discussion of the PartoPen Studies 2012-2013

Four PartoPen evaluation studies have been described in this chapter. The usability study helped refine the design of the PartoPen system, and provides an understanding of the occupational workflow of the system in which the system would be deployed. The nursing student study confirmed the hypothesis that PartoPen use instructions and decision support

would improve nursing students' scores on partograph completion tasks. The nursing student study also illustrated that the PartoPen system provides these benefits even with minimal training on PartoPen use. The maternity ward study examined the benefits of the PartoPen system in an actual clinical setting. Finally, the 2013 follow-up study illuminated several key points, and suggested several opportunities for future work in partograph evaluation, perceptions of tools designed to assist healthcare practitioners, and barriers to healthcare interventions in the development world.

At a high level, the project benefited greatly from attention to detail, and simple adjustments that were made to address important, but not immediately obvious, issues. Innovative technologies can provide complex functionality to address specific health issues, but the importance of simple, non-technological improvements to the overall system should not be ignored when evaluating the impact and usability of the solution. The PartoPen studies illustrate the benefits of having a rapid and flexible development process so that changes can be made quickly and effectively, the importance of budgeting additional time in the study design for the implementation of the technology, and the value of incorporating training into practice to reduce the time-intensive training costs for healthcare workers

4.5.1 Synthesis of PartoPen Study Results

Data from the maternity ward study do not generally exhibit significant differences in partograph completion rates between partographs completed with the PartoPens and those not completed with the PartoPens. In retrospect, this result is not surprising. The PartoPen system was designed to address training and data interpretation barriers that have been cited as significant obstacles to correct partograph use in developing countries. However, the PartoPen system was deployed at Kenyatta National Hospital, one of the leading training and teaching

facilities in Kenya. KNH has a highly trained and knowledgeable staff that is less likely to benefit from the training re-enforcement aspects of PartoPen use. The other cited barriers to partograph use, including staff shortages and lack of supplies, are not directly addressed by the PartoPen system, thus at KNH, any training reinforcement benefit the PartoPen provided was overshadowed by other barriers.

The positive results in the nursing student study demonstrate that the PartoPen is beneficial for partograph training for less-trained staff, or for students learning how to use the partograph. In a controlled environment like a classroom, where the primary focus is on the task of completing a form rather than safely delivering a baby, the PartoPen's training reinforcement and decision-support functionality are fully utilized. In the unpredictable and understaffed environment of the labor ward at KNH, the primary focus is on patients, not on paperwork, thus the design objectives of the PartoPen system did not align well with the primary focus of KNH nurses. The PartoPen maternity ward study design also did not adequately account for the myriad confounding factors present at KNH, including under-staffing issues, different birth rates between months compared, and the presence of (different groups of) nursing students in the labor ward during the intervention month, but not the control month. Unlike the PartoPen nursing student study design, the maternity ward study was not designed such that *only* the effect of the PartoPens on partograph completion could be measured. During subsequent analysis, study results were evaluated assuming an experimental study where nurses were given the intervention (the PartoPen) and the nursing students present in the labor ward were the control group. This was not an ideal study design, as the experimental and control groups were not well matched in terms of training, background, or experience. A more appropriate study design for this

environment would be a paired comparison of individual nurses' performance on partographs for similar labor types with and without the PartoPen during comparably busy shifts.

In an attempt to single out the impact of the PartoPens on various aspects of partograph completion, a fourth data analysis technique was used, but not described in the previous chapter due to inconclusive results. This fourth analysis attempted to use proxy measurements to assess the different pieces of PartoPen functionality – decision support, reminders, and use instructions – separately. Use instruction effectiveness was essentially the same score as the composite score in the first analysis because there were instructions for every partograph section, and each set of instructions detailed how often measurements should be taken and the symbols to use for each measurement. The reminder effectiveness was measured as a function of how many marks were made and the spacing between marks *only* for the sections that triggered reminders (fetal heart rate and cervical dilation). Finally, the decision support effectiveness was measured by first identifying partographs where the decision support would have been triggered (i.e., partographs where cervical dilation crossed the alert or action lines, partographs where fetal heart rate went above 170 or below 110, and partographs where 'M' was recorded for liquor.) However, the sample size for partographs meeting the decision support criteria was extremely low. In terms of clinical outcomes, a low sample size in this category is a good thing, but for measuring PartoPen effectiveness, the small sample did not illuminate any quantifiable differences in actions taken by nurses because of the decision support prompts.

The nurses reported in the paper survey that they considered partograph information to be important, and that they relied upon this information. Interviews with nurses additionally revealed that nurses considered the partograph an essential tool in the labor ward. However, the computer survey revealed that an incomplete partograph can still be useful, and that nurses were

able to correctly identify partographs that were incomplete or filled out incorrectly, suggesting that low partograph completion rates are not necessarily associated with a lack of diligence or aptitude among nurses. From this preliminary data, it may be efficacious for future researchers to examine the strength of the relationship between partograph completion rates and quality of care. Understanding the true nature of this relationship may be particularly complex at a short-staffed referral facility where other barriers, besides training, present significant obstacles to strict execution of care protocol.

The PartoPen studies at KNH provided quantitative and qualitative data on nurses' attitudes toward PartoPen usability. These studies also contributed to our understanding of various design issues, nurses' perceptions of the differences between a useful and a complete partograph, and preliminary data on the durability and infrastructure requirements of the PartoPen system. Together, these results will help inform future deployments of digital pen technology in healthcare settings.

The next chapter offers a subjective and personal discussion of several peripheral aspects of the PartoPen project, and is intended to be a reflective account of some of the less successful study design decisions and outcomes of this work. Chapter 5 is aimed at researchers beginning or continuing similar work, and was published first as a workshop submission to the 2013 Conference on Computer Human Interaction (CHI) held in Paris, and was included as a case study in the Graduate Student Guidebook published in Morgan & Claypool Publishers' Synthesis Lectures on Assistive, Rehabilitative, and Health-Preserving Technologies [23].

5. REFLECTIONS ON THE PARTOPEN PROJECT

This chapter presents personal reflections on the PartoPen project, which collectively are intended to provide practical guidance for researchers working at the intersection of technology, healthcare, and international development. The remainder of this section will provides an introspective discussion of some of the areas of the PartoPen project that were unsuccessful, and discuss why and how the study could have been conducted differently to avoid these failings.

5.1 Unanticipated Research Challenges

Section 5.1.1 describes a failed attempt to deploy the PartoPen system at a second study site, and Section 5.1.2 discusses some of the unforeseen challenges involved in maintaining and configuring a printer to produce the partograph forms, which proved to be more difficult than any aspect of deploying and maintaining the PartoPens themselves.

5.1.1 Pumwani Maternity Hospital: The Second Study Site

The first PartoPen study was intended to be conducted at two study sites: Pumwani Maternity Hospital (PMH) and Kenyatta National Hospital (KNH). While there was participant buy-in at both PMH and KNH, all of the prior feasibility studies had taken place at KNH, and the study was designed using observations and qualitative data from KNH only. In July 2012 we introduced the PartoPen at both KNH and PMH. The nurses at KNH immediately adopted the pens, and felt comfortable asking questions and suggesting changes. At PMH, the nurses had not been informed by the hospital administration that the pilot study was going to take place, and were skeptical about a young, white computer scientist with a "magic pen" asking them to change their routine. After a week of observation, some big differences between PMH and KNH emerged. First, at PMH, there are only two or three registered nurses on duty per shift, and medical students on their clinical rotations do the majority of the work. The stipulations of the

study design stated that only the nurses were to use the pens so that accurate before-and-after data could be collected, which would not be possible among students due to volume of students coming and going in the ward during any given week. Consequently, the study design severely limited the amount of data that was collected at PMH. On average, 80-100 babies are delivered at PMH every day, and a mere 50 data points were collected for PMH during the one-month pilot study. In addition to the "after" data being extremely scarce, the "before" data presented a significant and unforeseen challenge as well. The study design discussed how files from the month of June would be collected from the records offices at each study site to be used as baseline data for the study. However, not having spent adequate time at PMH before the study, it was quickly discovered that PMH's "records office" consists of several dozen plastic garbage bags filled with files from various months in no particular order (see Figure 25). Sufficient time and resources had not been allotted to undertake the task of finding and scanning the 2000+ files from June. In an attempt to salvage the invested efforts to implement the project at PMH, researchers concentrated on conducting qualitative interviews with nurses that focused on higher-level issues at the facility and recorded qualitative observations of PartoPen use in isolated cases.

Figure 25: A photograph of the overflow patient record storage at Pumwani Maternity Hospital.

The study designed for KNH was thus unsuccessful at PMH, illustrating that "scalability" is not simply achieved by increasing the number of study sites involved. A successful implementation of the project at both KNH and PMH would have started with a deep understanding of the processes and people *at each location*, and study designs that accommodated the existing conditions and cultures.

5.1.2 More Than Just PartoPens

During the June 2013 visit to KNH, I discovered that a printer failure had been the sole reason for discontinuing the use of the PartoPens the month before I arrived. The PartoPens themselves had been well maintained and continually used, but the unavailability of replacement printer parts, and a lack of replacement toner and paper, ultimately caused nurses to stop using the PartoPens in the labor ward. So much of the effort to implement the PartoPen system was focused on the digital pens and the nurses that the infrastructure required to sustain the printing operations in the records office was not sufficiently established.

The challenges of printing the dot paper illustrate an unexpected issue with the system as a whole, and has raised questions for future investigation around low-cost, high quality printing services and business models for producing and selling hospital forms. Overall, the PartoPens were well maintained and sustained by the staff at KNH, but complicated feedback loops between hospital departments, inadequate instructions for procurement of supplies, and the incorrect assumption that the printing aspect of the PartoPen project would be straightforward and self-sustaining, required nurses to discontinue using the PartoPen system after nine months of continuous use.

Health informatics interventions, especially in developing countries, are often consumed by the technological aspects of the project. We sometimes fail to recognize the benefit of addressing immediate and simple issues, which do not necessarily require technological intervention. The qualitative feedback received by nurses indicated that the cleaner PartoPen form with larger boxes for information entry considerably improved the usability and readability of the form. The cleaner form was simple to produce within the existing workflow and with existing equipment, and could have been done independently of the PartoPen project.

5.2 Advice for Fellow Researchers in ICTD and Health

During the PartoPen project, I derived several "rules of thumb" from my experiences. The advice outlined in this section is intended to be generalizable to most HCI work in healthcare settings, and is supported by specific examples from the PartoPen project.

5.2.1 Time Management

It is difficult to ask research participants, especially busy nurses in understaffed hospitals, to take an hour or two to talk about a project in which they may or may not have any interest or investment. However, if you make yourself available and present, it won't take as long as you think for people to start asking you questions, and becoming interested in what you're doing in their hospital. It is common for researchers to believe that budgeting time for "sitting around" is not going to pay off in terms of their grant obligations or deliverable deadlines. However, if you do not make the initial investment in your participants and the environment in which they work, you usually have lost sight of the larger goal altogether. So scale your study to account for this necessary investment, while still staying true to deadlines and financial constraints.

Budgeting extra time – a three-month trip to Kenya instead of a one-month trip – proved invaluable to the PartoPen project. I used the extra time to accomplish many things, including administrative tasks that were simplified by being there in person. I spent most of my time in the labor ward with nurses, talking with them, helping them perform patient in-take when staff numbers were low, and asking questions when time permitted. One of the benefits of the PartoPen project is that the pen itself is low profile, and a valuable research and note-taking tool in and of itself. When I spent time in the labor ward, I would use a digital pen to write down observations and take notes. Simply using the pen in front of the nurses drew their attention, caused them to ask a number of insightful questions, and illustrated the simplicity and the

broader potential of the pen. By using the pen myself, I was also able to decrease the perception of additional work often associated with the introduction of a new technology. Although it seemed like I was just taking notes, this use promoted communication and interest in the project.

During the three weeks I spent observing and interacting with the staff prior to the start of the study, I tasked myself with finding out three things about each nurse beyond obvious demographic characteristics. Discovering these things about each nurse allowed me to better understand their values and incentive systems. For example, during an afternoon tea break (which I have found is the optimal time for getting to know your study participants and getting answers to your questions) I spoke with a nurse who eventually told me: "The pen needs a cap! I don't have time to wash my uniform every night and the pen marks are hard to get out! If you do my laundry, I'll use it." Most of the nurses who work at KNH live about two hours, by bus, away from the hospital, which means that in addition to their 8-12 hour shifts, they are stuck in traffic for another four hours. Adding makeshift caps to the pens noticeably shifted the mood among the nurses. By learning where the nurses lived, and how they commuted to work each day I discovered an underlying problem with the design of the system, addressed it, and did not infringe on one of the things they truly value: their time.

5.2.2 Do More Than the Research Requires

This section discusses the benefits of helping your study participants in an immediate way, regardless of whether providing that help falls in line with your overall research agenda. By spending time with research participants, asking questions, and observing the environment in which you will be conducting your research, you will begin to understand the necessary skills for completing various tasks. Undoubtedly, there will be tasks that you are capable of doing given your current skills. By offering immediate assistance with tasks you are qualified to do, you

accomplish several things. First, you illustrate your competence to the people you will be working with. Second, by learning to do the work that your research participants do every day, you will develop respect for them and the specific skills they have. Also, by successfully doing some of the work that they do every day, you will gain participants' trust. Third, by actually performing various tasks within the healthcare setting, you develop an intimate knowledge of detailed processes that often seem obscure when observed from the outside. Deep knowledge of specific processes within the clinic will allow you to gain a more complete picture of problems and areas for improvement that your research may be able to directly address. Getting to know your participants, and spending a great deal of time in the environment you are working in accomplishes many things; however, if you are not providing any valuable service or insight for long periods of time, there is a strong possibility that you will become a harmful distraction or an annoying, question-asking obstacle for people trying to do their work. By becoming a valuable contributor within the existing clinical workflow, you will be able to learn about your participants in an interactive way on an equal playing field and help them with their work instead of getting in their way.

My first extended visit to KNH in March 2012 was intended to be a trip solely for observation. On the first day, no one seemed interested in me or why I was there. Three hours went by, and a few nurses had said 'hello'. One nurse brought me tea around noon. On the second day, I returned to the labor ward, and everyone seemed surprised to see me. Now, I realize that this is a very common occurrence – they don't expect you to come back. It makes sense in a place where so many non-governmental organizations (NGOs), donors, and researchers come and go, promising changes, and failing to deliver; trust takes time and follow-through to develop.

The initial lack of communication, and my unfamiliarity with the terminology of the labor ward, made it difficult to understand labor ward processes. I started writing down all the words I didn't know, and asked during tea breaks what they meant. By the end of the week, I was helping with patient intake, making patient files with all of the appropriate forms, and occasionally answering the phone (my Swahili was getting pretty good at this point). It was much easier to pinpoint where I could add immediate value for the nurses once I understood the medical language they were speaking. Creating a dictionary is a valuable tool that can simplify your research and contribute to your unique and highly specific understanding of the issues you are interested in.

In cases where it is not as clear where you can provide value, two things will always apply. First, show up. This is applicable to every HCI research area in any part of the world. Second, in healthcare there are always patients and staff who can use a little assistance or a kind word of encouragement. Both are powerful illustrations of commitment and humility – two characteristics that will accelerate your research and remind you of the underlying reasons you do the work you do.

5.2.3 A Lesson in Humility

In healthcare, where patients' lives are often at stake, there is no amount of financial constraints, or donor expectations, or deadlines that can justify your research negatively impacting the health and well being of your research subjects. The growing number of FailFaires[2] and papers documenting the failures of development projects indicates the gradually shifting culture, which values "do no harm" policies over data collection, at all costs. Entering a

[2] http://failfaire.org/about/

healthcare setting should be a humbling experience, and if you don't check your ego at the door, it won't be long before it gets checked for you.

I learned early in the PartoPen project that it is detrimental to associate yourself so closely with your research that everything becomes personal. During my initial usability tests in March 2012, several aspects of the PartoPen functionality were underscored as clearly unusable. In the first iteration of the PartoPen project, the pen emitted audio when a nurse recorded an alarming measurement. The audio was recorded in my voice and was only played once. The first nurse to use the pen said something along the lines of "I can't understand a word this thing is saying…and I think what it said was wrong!" My first impulse was to retort, "It's not wrong! That's exactly what the WHO user manual on partograph use says! And I spoke so clearly and slowly; how can it be hard to understand what I was saying?" This is obviously the wrong response. Ego slightly bruised, I returned to the drawing board that night, and realized that the WHO manual was in fact inaccurate given the current version of the partograph that nurses were using. In addition, it became clear that it was difficult for the nurses to understand my voice even without it being recorded on the pen. I changed the audio prompts to text displays on the pen's display, accompanied by a "ring-tone" from the pen's speaker. The new design was well received, and the nurses expressed their appreciation for the quick fix. Seeing the quick change based on their feedback also encouraged the nurses to suggest other design changes and to be more vocal and honest about the project.

In an academic environment like graduate school, it is easy to become convinced that the important deliverables are publications with real data and statistical analysis, convincing answers to all of the questions committee members could possibly ask, and "expert" status in the microscopic body of knowledge you will produce. However, I find it useful to make a second

list, which helps me balance the urgency to complete academic requirements with the realities of my fieldwork environment. My list usually contains things that I will personally feel a sense of accomplishment for completing. The first iteration of my personal PartoPen list included: know all of the nurses' names by the time I leave; practice my Swahili even though everyone speaks English; and don't faint in the delivery room. The second iteration was more specific, and included performing specific project-related tasks like buying and installing a new printer and supplying it with ink and paper; capacity building activities like teaching IT staff how to program the digital pens and collect data; and personal goals like trying out recipes the nurses gave me, and printing pictures of the nurses for them. Very few of the things on these lists, if performed in isolation, would contribute to writing my dissertation or publishing my next paper; however, by doing the things on this list, I never found myself in a situation where getting the data at all costs was the only thing that defined my work.

When I left Kenya in August 2012 I had collected two months of partographs, 50 surveys, and two notebooks of qualitative observations. More notably, the labor ward at KNH continued to use the PartoPen system, which is currently run and managed entirely by hospital staff and labor ward nurses. By following the lessons discussed in this chapter, I was able to create a system that better fit the needs of the labor ward staff, without introducing extra work, training, or financial burdens. A recent letter from KNH administration praised the PartoPen system for improving the number of completed partographs in patient files, and for the higher quality patient care attributed to the PartoPen increasing awareness of labor monitoring practices. The current success of the PartoPen project is largely due to the genuine relationships I was able to develop during my fieldwork by showing up, being useful, and quickly responding to feedback without taking the inevitable critiques personally.

6. CONCLUSIONS AND FUTURE WORK

Two-and-half years of work on the PartoPen project have demonstrated the potential of digital pen technology to impact healthcare education and clinical operations. The PartoPen studies at KNH have also revealed many complexities of the maternal healthcare system in Kenya that were not primary research areas of this project. However, one of the key contributions of this research is a better understanding of the broader context of healthcare in developing countries, and the unique challenges of implementing technology solutions in such a multi-faceted environment. Section 6.1 elaborates the broader context in which the PartoPen system is deployed, and highlights the myriad issues facing the healthcare system in Kenya. These issues led to the future work discussed in Section 6.2.

6.1 Maternal and Child Health Technical Working Group Meeting

During the June 2013 study the PartoPen project was presented at the Maternal and Child Health Technical Working Group (MCH TWG) meeting in Nairobi. The meeting consisted of policy makers, Ministry of Health members, NGO partners and organizations including USAID, MChip, and WorldVision. The main topic at the meeting was the recent government mandate for free maternity services (antenatal, delivery, and postnatal care) nationwide. In March 2013, the newly elected government declared that within 100 days of taking office, free maternity care would be available to all women in Kenya. The recent transition to free maternity services has left health centers and staff scrambling. While free maternity care will draw more women to deliver in health centers and receive appropriate before and after care, the challenges associated with free care are numerous. Some of the high level concerns raised at the meeting included severe understaffing, insufficient funds for complicated patient cases, and a lack of infrastructure and space. One obstetrician noted that health workers in overcrowded facilities are being

wrongly accused of abuse and being taken to court by patients and their families, when in actuality, the "abuse," which was described as patients having to deliver on the floor or share beds with up to two other patients, is a direct result of the health system being unprepared to absorb the influx of patients coming to receive free maternity care. Patients are also inclined to deliver and receive care at the most prestigious public hospitals, like Kenyatta National Hospital, causing a disproportionate patient volume across health centers. At KNH alone, the number of deliveries has increased by 50%, and the number of elective cesarean sections has increased by more than 100%, since the inception of the free maternity care plan. The KNH labor ward is designated to handle complicated referral cases, but has seen a dramatic increase in uncomplicated patients simply wanting to deliver at a facility that is well equipped. The strain on the staff of KNH was evident when, on Friday June 21st 2013, the nurses and staff at KNH participated in a general strike. The goal of the strike was to push the government to follow through on a wage increase promised in 2009 that has not yet been implemented. The strike lasted for a day and a half, but during that time hundreds of patients were turned away and sent to other facilities.

Dr. Ong'ech, assistant director of reproductive health at KNH, spoke at the meeting on behalf of KNH and discussed the unforeseen costs, which were not explicitly outlined in the proposed budget for free maternity care. These include ectopic pregnancies and unsafe abortions, which are results of pregnancy, but which may or may not be funded under the new plan. The new budget specifies 2500Ksh (about $30 USD) per patient at dispensaries, 5000Ksh at district level hospitals, and 20,000Ksh at referral hospitals like KNH. However, some of the procedures that KNH is designed to handle (e.g., renal failure, cardiac patients, postpartum hemorrhage, etc.) and the associated costs of hospital stays and equipment can amount to hundreds of thousands of

Kenyan shillings. Kenya was previously organized into districts, but is now split into counties. The new county system is similar to the system used in Ethiopia and Somalia, where national policy is more administrative in nature, and the counties are responsible for determining their own funding allocations and priorities for the healthcare sector. There did appear to be consensus among meeting members regarding the degree of control that counties should exercise over funding or research collaborations with NGOs.

The high level message of each presentation was that quality of care must not be sacrificed in the presence of high patient volumes. In the words of one Ministry of Health official, "We must not simply change the place of maternal mortalities from the home to health care facilities." Nurse-midwives may not be permanently stationed in the labor ward, and may be rotated between departments (e.g., casualty, orthopedics, etc.). This practice does not allow these nurse-midwives to hone their midwifery skills. One of the key suggestions proposed at the meeting was to revive midwife-specific training colleges, and to elevate the general perception of a career in midwifery.

A secondary concern was transportation. Talking about the traffic in Kenya is like talking about the rain in Seattle. Severe traffic jams and slow-downs have a significant impact on the timeliness and quality of care. Patient referral has also suffered. Patients often may be received at the referral facility beyond the point of care, or may not reach it at all. One audience member described having to travel over 150km between the nearest health centers in northern Kenya. Voucher programs were proposed, and innovative motorbike ambulances were briefly mentioned, but emergency transportation is one area of immense concern, and an area ripe for high-impact innovations.

The PartoPen presentation at the meeting discussed the technology itself, and the student

and maternity ward studies that were conducted in June-August 2012. The majority of the questions after the presentation focused on sustainability, especially around procuring the necessary printer parts and recurrent supplies - toner, paper, etc. There was also concern about the usefulness of the PartoPen in high volume facilities, where the high nurse-to-patient ratio makes it nearly impossible to complete a partograph correctly for every patient. In a discussion with several of the obstetricians in attendance at the meeting, it was clear that a thorough examination of a patient upon admission can determine the course of action for that patient, and effectively triage patient cases. It would follow then that a partograph with a complete record at the time of admission might be just as beneficial as a fully completed partograph. As one woman mentioned, "Practice is so different from theory. If the nurse uses the initial exam to perform the necessary practices, and the women and child are healthy after delivery, then it is a success. A fully completed partograph isn't always necessary."

The issue of maternal and child health in Kenya is complex and challenging, and there are many unanswered questions about access and funding. The reactions to the PartoPen were mixed, largely due to the extreme challenges facing maternal health, but many innovators and entrepreneurs present at the meeting were eager to implement the PartoPen at their facilities and explore what such extended functionality could do to improve patient referral, midwife training, and real-time decision support.

The MCH TWG meeting highlighted how many motivated and innovative individuals are working toward reducing maternal and child mortality worldwide. The meeting also illustrated how much work there is still left to do to improve maternal and child health in Kenya and across East Africa.

6.2 Future Work

One of the key conclusions of the PartoPen study is that the PartoPen, by design, addresses teaching and training barriers to partograph use, and does not directly address understaffing and resource shortages. In light of this conclusion, the next step in continuing this research should be to implement and evaluate the PartoPen system at more rural clinics, which receive fewer patients, but typically have lower levels of staff training.

Working with referral hospitals in the next phase of the PartoPen project will also motivate the design and development of an information referral system for patients who are transferred between hospitals. The issue of patient referral in Kenya was a common theme in interviews and researcher observations. Patients arriving past the point of effective care (almost always without any record of the labor up to that point) is one of the primary causes of maternal death in Kenya. Leaving aside the traffic-related barriers to patient transportation, there is an opportunity to improve the delivery of patient information to the referral hospital through a digital channel. The PartoPen was built using Livescribe's Echo digital pens, which do not have networking capability. However, since the PartoPen project began, Livescribe has released a Wi-Fi-enabled digital pen that could be used to transfer digital data from one hospital to another. In January of 2013, I spent a week at Livescribe headquarters in Oakland, CA to begin the design of a networked referral system using the Wi-Fi pens. With the help of several Livescribe employees, I was able to successfully upload digital records to a cloud-based repository and download them to a different digital pen. The feasibility of this new effort will depend largely upon Livescribe's willingness to release the software tools and development environment to third party developers (or at least to the PartoPen project).

The results of the nursing student PartoPen study illustrate that the PartoPen offered significant benefits (independent of training in the use of the system) related to students learning to correctly use the partograph. One potentially promising area of future work would be to expand the use of the PartoPen in training environments, and to allow students to use the PartoPens for self-study outside of the classroom. The Livescribe pens are sold primarily to students and academic institutions, so it is no surprise that the educational benefits of digital pen technology can also be applied in developing world healthcare training contexts. Custom software applications could be easily developed to accommodate a number of paper forms, including tests or practice worksheets for students to supplement their in-class learning. If classroom and student use of the PartoPens is widely adopted, numerous possibilities arise for creating transitional tools for use in the classroom *and* in the clinic. Software could adapt to a users' ability and skill level as they progress. Different forms or worksheets could be loaded onto the pen as modules, which would add a time component or 'mastery' concept to the acquisition and reinforcement of concepts being taught.

Other educational opportunities for the PartoPen exist in local engineering and computer science schools. The "Fab Lab" (an engineering and IT department) at the University of Nairobi has been in contact with the PartoPen team to initiate discussions around using digital pens as platforms for class projects in software development. The implementation of the PartoPen and its associated software development tools at institutions like the Fab Lab could provide a valuable local pipeline of custom application developers for digital pens. Such a resource has the potential to increase the feasibility of wide deployment of digital pens in Kenya across multiple sectors.

During the PartoPen studies, nurses and students made several feature requests. KNH administration suggested using the PartoPens to improve accountability among nurses. The idea

is to incorporate a signature or timestamp to be captured by the pen, which would link the nurse completing a certain section of the partograph (as partographs are often used by more than one nurse, especially for long labors), to that partograph. Thus, in the event of a maternal or fetal mortality, a more in-depth review could be done with the nurse(s) who actually completed that form.

The timestamps captured by the pen could also be used to detect retroactive completion rates of the partograph form. There is no specific benefit to using the partograph after a delivery. A nurse could just as easily (or more easily) record retroactive information on a notecard in the patient file, rather than painstakingly completing the entire partograph form after the delivery. In addition, the information on the partograph form, if completed retroactively, is usually drawn from other places in the patient file, indicating that this information is redundant. Capturing the rate of retroactive completion, therefore, would provide greater insight into the benefit of using the partograph, and its associated impact on maternal and fetal outcomes, if any. However, retroactive completion has not been well documented because of the difficulty of extracting this information from an already completed form. However, if the form could be 'recreated' in real-time using the digital information stored on the PartoPen, it would be simple to determine if the partograph was completed during the labor or after. Identifying retroactive completion could be useful for determining if the partograph is being used as intended, or if the decision support and real-time benefits of using the form are not being used.

More generally, there is an opportunity for digital pen technology to integrate into healthcare in developed countries as well. The mandated use of electronic medical records (EMRs) in the United States has left many care providers struggling to choose a system, learn it, and implement it without sacrificing quality care to patients. An expanded version of the

PartoPen system could allow the continued use of paper in hospital offices, while providing the automatic integration with backend EMR systems while reducing timely transcription and the errors associated with it.

6.3 Summary of Dissertation Contributions

The principal contributions of this dissertation include:

1) A novel digital pen-based hardware and software system that helps address the issues of poor partograph completion and accuracy in developing countries, and that integrates available digital pen technology with existing paper-based labor monitoring tools;

Chapter 3 describes the hardware and software components of the PartoPen system. The PartoPen system uses readily available digital pens from Livescribe, Inc. and the associated Anoto dot pattern paper to provide unique software functionality for nurses in the developing world. The PartoPen enhances the partograph by providing use instructions, decision-support, and time-based reminders. The PartoPen system is designed to reinforce birth attendant training and overcome barriers facing partograph use and quality labor monitoring in the developing world.

2) An improved rubric for completed partograph evaluation that emphasizes elements of the partograph that are clinically relevant;

Chapter 4 describes a new method for partograph evaluation that scores partographs by section according to the number of measurements taken, symbol correctness, and spacing correctness between measurements. Previous work on partograph evaluation has used more subjective methods for evaluating partograph completeness. The PartoPen evaluation rubric, in contrast, provides a replicable and objective method for evaluating partographs. Standardized evaluation of partographs facilitates larger scale studies that can more definitively assess the

medical benefit of the partograph, and can identify those aspects of the current partograph that should be updated to reflect current science, local conditions, and other factors.

3) A multi-phase analysis of the qualitative and quantitative benefits of PartoPen use in maternity clinics and nursing classrooms in urban Kenya;

Chapter 4 describes four PartoPen studies that were conducted to examine various aspects of the PartoPen system. The results of these studies support and motivate continued research in the area of using digital pen systems in the context of healthcare for development, while illuminating a complex array of barriers and obstacles facing the delivery of quality and timely maternity care in the developing world.

4) A set of recommendations that provide practical guidance for improving labor monitoring in developing countries; and

Chapter 5, a personal reflection of the successes and failures of the PartoPen project, provides advice and guidance for researchers seeking to work in this space.

5) An improved understanding of the relationship between partograph completion and clinical outcomes.

This dissertation highlights a need to re-examine the perceived relationship between partograph completion and quality of care. By implementing the PartoPen system at KNH, many complex issues surrounding the healthcare system in Kenya, which had not been accounted for in the initial study design, were identified. By highlighting these complexities, this dissertation provides new insights at the intersection of healthcare, technology, and development.

6.4 Conclusions

It is generally believed that the partograph, when used correctly, can reduce the number of preventable maternal and fetal deaths in the developing world. Chapter 2 highlights several

studies that support this conclusion. However, correct use of the partograph alone does not translate to a reduction in the number of preventable maternal and fetal deaths. If a partograph is filled out correctly, the woman was likely admitted to the hospital before active labor had started, or just when it had started (indicating no referral or transportation or financial problems); she was monitored every half hour by a skilled birth attendant (indicating no staff shortages); and she received the interventions that she needed when she needed them (indicating no resource shortages). Therefore, a correctly completed partograph is also evidence that environmental and social circumstances did not adversely impact delivery. The relationship between partograph completion and positive maternal and child outcomes may in fact be representative of the relationship between resource availability (for both patients and healthcare providers) and positive maternal and child outcomes.

The initial objective of the PartoPen maternity ward studies was to examine the impact of digital pen technology on *partograph completion*. This objective assumed that a primary barrier to partograph completion was a lack of training and knowledge on how to complete and interpret the form. However, the highly skilled staff at KNH did not lack in training or knowledge, but rather, suffered from staff and resource shortages, which the PartoPen was not designed to address. Despite the disparity between the study goals and observed study site realities, several important observations were made that may contribute to future work in this area.

The PartoPens deployed at KNH were successfully used and sustained for over nine-months of continuous hospital use. This illustrates the robustness of the system, as well as a willingness among nurses to use the PartoPens on a daily basis. The PartoPen maternity ward studies also helped identify the environmental and physical challenges present in the KNH labor ward, and illustrated both the challenges and opportunities that arise when deploying a digital

pen software system in a maternity ward setting. The results of this study are encouraging for the continued and expanded use of digital pen systems in healthcare, and stress the need for more in-depth and well-designed studies in this area.

On the final day of the maternity ward study at KNH, several television news stations and local newspapers visited the labor ward to interview nurses about the PartoPen system (see Figure 26). The coverage of the PartoPen system aired on three Kenyan news stations, and was reported in several newspapers and online media sources. There is tremendous enthusiasm in Kenya around improving maternity services and maternal and child health. At all levels of healthcare, from the Ministry of Health to the nurses in the labor ward, there is a general openness to using, customizing, and creating innovative solutions to combat serious health issues. Despite the complexities involved in healthcare systems, the creativity and enthusiasm for innovation that was demonstrated during the PartoPen studies by hospital staff, nursing students, and patients illustrates that the foundation for positive change already exists. More than anything, the PartoPen project illustrates that healthcare processes are not static, and that healthcare providers and consumers are open to new ways of bettering the health of the community in which they serve and live.

Figure 26: Demonstration of the PartoPen system at Kenyatta National Hospital for Kenyan television and newspaper crews.

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APPENDIX A: Nursing Student Study PartoPen Worksheet

PartoPen Project Pilot – June 2012

Participation in this study is voluntary. Participating in this study will not affect your academic record in any way.

If you have any questions or concerns about the study, please contact Heather Underwood at: heather.underwood@colorado.edu, or by phone at 0705222988 or +13609813928.

Year of Study: _____ Gender: _____ Age: _____

How confident are you in your ability to accurately complete a partograph form:

1	2	3	4	5
Not Confident				Extremely Confident

Suggestions/Feedback:

_____
_____
_____
_____
_____
_____

CASE 1:

Record the following on the partograph form:

- Mrs. A. was admitted at 09:00 on 12.5.2011
- Membranes ruptured 04:00
- Gravida 3, Para 2+0
- Hospital number 7886

Q: When should a partograph be started?

_____

_____

Upon admission:

- The cervix is 5 cm dilated *(Mrs. A is in the active phase of labor; plot the cervical dilation **on the Alert line** with an X. Tap "Cervix (cm) [Plot X]" for more information. Tap multiple times on "Cervix (cm) [Plot X]" to continue receiving information.)*

- The fetal head is 3/5 palpable above the pelvic brim (*tap on "Descent of head [Plot O]" for more information)*

- There are 3 contractions in 10 minutes, each lasting 20–40 seconds *(tap on "Contractions per 10 mins" for more information on how to record contractions on the grid – recordings will look similar to a bar chart; duration patterns are illustrated in the Contraction legend on the left hand side of the form.)*

- FH 120 *(Fetal heart rate (FH) is recorded with a single dot on the vertical line corresponding to the time the measurement was taken; tap on "Fetal heart rate" for more information)*

- Membranes ruptured, amniotic fluid clear *(The time when membranes ruptured is recorded at the top of the form. Membrane state, if not ruptured, is recorded in the "Amniotic fluid" grid; tap "Amniotic fluid" to hear more information)*

- Sutures of the skull bones are apposed (*i.e., just touching each other; tap "Moulding" for more information on how to record suture position)*

- Blood pressure 120/70 mm Hg *(Blood pressure is recorded with a vertical double-headed arrow; tap "BP" for more information)*

- Temperature 36.8°C *(tap "Temp °C" for more information)*

- Pulse 80 per minute *(tap "Pulse" for more information)*

- Urine output 200 mL; negative protein and acetone *(tap "Urine" for more information)*

Q: What phase of labor is the woman in?

Q: At what time should the next vaginal examination be made?

Q: At what time should fetal heart rate be measured next?

Q: At what time should contractions be measured next?

Q: At what time should pulse be measured next?

Q: At what time should blood pressure be measured next?

Record the following observations as the woman progresses through labor:

09:30 FH 120, Contractions 3/10 each 30 sec, Pulse 80
10:00 FH 136, Contractions 3/10 each 30 sec, Pulse 80
10:30 FH 140, Contractions 3/10 each 35 sec, Pulse 88
11:00 FH 130, Contractions 3/10 each 40 sec, Pulse 88, Temp 37
11:30 FH 136, Contractions 4/10 each 40 sec, Pulse 84, Fetal head is 2/5 palpable
12:00 FH 140, Contractions 4/10 each 40 sec, Pulse 88
12:30 FH 130, Contractions 4/10 each 45 sec, Pulse 88

At 13:00:

- FH 140, Contractions 4/10 each 45 sec, Pulse 90, Temp 37
- The fetal head is 0/5 palpable above the pelvic brim
- The cervix is fully dilated
- Amniotic fluid clear
- Sutures apposed
- Blood pressure 100/70 mm Hg
- Urine output 150 mL; negative protein and acetone

At 13:20: Spontaneous delivery of a live female infant; weight 2,850g. *(record this information in the summary of labor at the bottom of the partograph)*

CASE 2:

- Mrs. C. was admitted at 10:00 on 12.5.2011
- Membranes ruptured 09:00
- Gravida 4, para 3+0
- Hospital number 6639

Upon admission:

- The cervix is 4 cm dilated
- The fetal head is 3/5 palpable above the pelvic brim
- There are 3 contractions in 10 minutes, each lasting 30 seconds
- FH 140

- Amniotic fluid clear
- Sutures apposed
- Blood pressure 120/70 mm Hg
- Pulse 80 beats per minute
- Temperature 36.8°C
- Urine output 200 mL; negative protein and acetone

Record the following on the partograph as the woman progresses through labor:

10:30 FH 130, Contractions 3/10 each 35 sec, Pulse 80
11:00 FH 136, Contractions 3/10 each 40 sec, Pulse 90
11:30 FH 140, Contractions 3/10 each 40 sec, Pulse 88
12:00 FH 140, Contractions 3/10 each 40 sec, Pulse 90, Temp 37, Head 3/5
12:30 FH 130, Contractions 3/10 each 40 sec, Pulse 90
13:00 FH 130, Contractions 3/10 each 40 sec, Pulse 88
13:30 FH 120, Contractions 3/10 each 40 sec, Pulse 88

At 14:00:

- FH 130, Contractions 4/10 each 45 sec, Pulse 90, Temp 37, Blood pressure 100/70
- The fetal head is 3/5 palpable above the pelvic brim
- The cervix is 6cm dilated, amniotic fluid clear
- Sutures overlapped

14:30 FH 120, Contractions 4/10 each 40 sec, Pulse 90, Amniotic fluid clear
15:00 FH 110, Contractions 4/10 each 40 sec, Pulse 88, Amniotic fluid is meconium stained

Q: What action should be taken at this time?

_____

15:30 FH 100, Contractions 4/10 each 45 sec, Pulse 100
16:00 FH 90, Contractions 4/10, each 50 sec, Pulse 100, Temp 37

At 16:30:

- FH 90, contractions 4/10 each 50 sec, Pulse 110
- Cervix is 6 cm dilated
- Fetal head is 3/5 palpable above the pelvic brim
- Amniotic fluid is meconium stained
- Sutures overlapped
- Urine output 100 mL; protein negative, acetone 1+

At 17:00: Cesarean section performed; live female infant with poor respiratory effort, Wt. 4,850g. *(record this information in the summary of labor at the bottom of the partograph)*

CASE 3:

- Mrs. B. was admitted at 10.00 on 2.5.2000
- Membranes intact
- Gravida 1, Para 0+0
- Hospital number 1443

Upon admission (10:00):

- The cervix is 4 cm dilated
- The fetal head is 5/5 palpable above the symphysis
- There are 2 contractions in 10 minutes, each lasting less than 20 seconds
- FH140
- Membranes intact
- Blood pressure 100/70 mm Hg
- Temperature 36.2°
- Pulse 80 per minute
- Urine output 400 mL; negative protein and acetone

Q: What phase of labor is the woman in?

Q: At what time should the next vaginal examination be made?

Q: At what time should fetal heart rate be measured next?

Q: At what time should contractions be measured next?

Q: At what time should pulse be measured next?

Q: At what time should blood pressure be measured next?

Plot the following information on the partograph:

At 10:30 FH 140, Contractions 2/10 each 15 sec, Pulse 90
At 11:00 FH 136, Contractions 2/10 each 15 sec, Pulse 88, Membranes intact
At 11:30 FH 140, Contractions 2/10 each 20 sec, Pulse 84
At 12:00: FH 136, Contractions 2/10 each 15 sec, Pulse 88
At 12:30: FH 136, Contractions 1/10 each 15 sec, Pulse 90
At 13:00 FH 140, Contractions 1/10 each 15 sec, Pulse 88
At 13:30 FH 130, Contractions 1/10 each 20 sec, Pulse 88

At 14:00

- FH 140, Contractions 2/10 each 20 sec, Pulse 90, Temp 36.8, Blood pressure 100/70
- The fetal head is 5/5 palpable above the symphysis pubis

- Urine output 300 mL; negative protein and acetone
- Membranes intact

Q: What is the suggested next step at this point, based on the data you have entered?

At 14:00

- The cervix is 4 cm dilated, sutures apposed
- Labor augmented with oxytocin 5 units per 1 liter *(i.e., 5 U/L)* IV fluid at 10 drops per minute (dpm)

At 14:30 FH 140, Contractions 2/10 each 30 sec, Pulse 88, Infusion rate increased to 20dpm

At 15:00 FH 140, Contractions 3/10 each 30 sec, Pulse 90, Infusion rate increased to 30 dpm

At 15:30 FH 140, Contractions 3/10 each 30 sec, Pulse 88, Infusion rate increased to 40 dpm

At 16:00 FH 144, Contractions 3/10 each 30 sec, Pulse 92, Infusion rate increased to 50 dpm, cervix is 6cm dilated, sutures apposed, fetal head is 2/5 palpable

At 16:30 FH 140, Contractions 3/10 each 45 sec, Pulse 90, Maintain at 50 dpm
At 17:00 FH 138, Contractions 3/10 each 40 sec, Pulse 92, Maintain at 50 dpm
At 17:30 FH 140, Contractions 3/10 each 45 sec, Pulse 94, Maintain at 50 dpm
At 18:00 FH 140, Contractions 4/10 each 50 sec, Pulse 96, Maintain at 50 dpm
At 18:30 FH 144, Pulse 94, Contractions 4/10 each 50 sec, Maintain at 50 dpm

At 19:00

- FH 144, Contractions 4/10 each 50 sec, Pulse 90
- Cervix is fully dilated
- Fetal head is 0/5 palpable

At 19:30 Spontaneous delivery of live male infant, Wt. 2,654g

APPENDIX B: Maternity Ward Study Nurse Survey

PartoPen Pilot Study – Participant Survey – August 3, 2012

Please complete the following questions:

Age: _____ Gender: _____

1) How many years have you worked as a nurse midwife? _____

2) How many years have you worked at Kenyatta National Hospital? _____

3) Where did you receive your nursing training?
_____

4) On average. how many patients in active labor do you care for during one **day** shift? (Circle one of the ranges below)

0-3 3-5 5-7 7-10 >10

5) On average, how many patients in active labor do you care for during one **night** shift? (Circle one of the ranges below)

0-3 3-5 5-7 7-10 >10

6) **Before** the PartoPen project, what percentage of your patients did you complete a partograph for?

0-25% 25-50% 50-75% 75-100%

7) **After** the PartoPen project, what percentage of your patients did you complete a partograph for?

0-25% 25-50% 50-75% 75-100%

8) On a scale of 1 – 10, rate your satisfaction with the PartoPen project in terms of usability (i.e., ease of use, functionality, enjoyability, instruction clarity, etc.)

1	2	3	4	5	6	7	8	9	10
Unsatisfied									Extremely Satisfied

9) On a scale of 1 – 10, rate your satisfaction with the PartoPen project in terms of usefulness (i.e., level of patient care, level of job satisfaction, amount of time spent on tasks, etc.)

1	2	3	4	5	6	7	8	9	10
Unsatisfied									Extremely Satisfied

10) Please provide any general or specific feedback you have on the PartoPen project. This feedback will be used to improve the PartoPen system for future deployments.

Thank you!

APPENDIX C: KNH Follow-up Study Paper Survey

KNH PartoPen Study – Participant Survey – June 2013

Please provide answers for the following questions:

Name: _____ Age: _____ Gender: _____

1) Did you participate in the PartoPen study in July and August 2012? YES NO

2) What is your level of experience using the PartoPens? (circle a choice below)

1	2	3	4	5
No experience				Expert

3) How much do you rely on the partograph to make decisions about patient care? (circle a choice below)

1	2	3	4	5
I don't use partograph information at all				I **only** use partograph information

4) Please number the following partograph sections in order of importance from 1 to 24, where 1 is the first thing you look at on a partograph to make patient care decisions, and 24 is the partograph section that you need the least to feel confident making patient care decisions.

Patient name and age	_____
Patient gravida and para	_____
Date of admission	_____
Time of admission	_____
Time of ruptured membranes	_____
Fetal heart rate	_____
Liquor	_____
Moulding	_____
Cervical dilation	_____
Descent of fetal head	_____
Contractions (duration)	_____
Contractions (frequency)	_____
Oxytocin administration	_____
Drugs given & IV Fluids	_____
Pulse	_____
Blood Pressure	_____

Temperature _____
Respirations _____
Urine (protein) _____
Urine (acetone) _____
Urine (volume) _____
Summary 1st Stage _____
Summary 2nd Stage _____
Summary 3rd Stage _____

5a) Are there certain patients that do not need a partograph? YES NO
5b) If yes, what type of patients do not need a partograph?

_____
_____

6a) What kind of labors/births benefit the most from correct partograph use? (circle all that apply)

SVD CS IUFD Referral Other?

6b) For the answers you circled in 6a, please explain why these types of births benefit the most from correct partograph use.

_____
_____
_____
_____
_____
_____

7a) Have there been any changes in the labor ward because of the PartoPen? YES NO

7b) What are they? How did they affect you?

_____
_____
_____
_____
_____

8a) Have there been any problems with the PartoPen? YES NO

8b) If yes, what are they? How did they affect you?

_____
_____
_____
_____
_____

9) Now that you have used the PartoPens for several months, what would you like the next steps to be in the project? (Please list any other comments about the PartoPen project here).

_____
_____
_____
_____
_____
_____
_____
_____
_____
_____
_____
_____
_____
_____
_____
_____

APPENDIX D: PartoPen Grading Rubric and Evaluation Guidelines

			Date Admitted:		Date Delivered:								
IP Number:			Time Admitted:		Time Delivered:		Time Diff	0:00	# of 1/2 hr. Measure	1	# of 4 hr. Me	0	
	Marks are there? (possible)	Complete Percentage	Marks are accura (possible)	Symbols correct? (possible)	Plotted on correc (possible)	Spacing?	(possible)			TOTAL	TOTAL PTS POSSIBLE		
Patient Info	8	0.00%								0	8	0.00%	
FH	1	0.00%		0		0				0	1	0.00%	
Liquor	0	#DIV/0!		0		0				0	0	#DIV/0!	
Moulding	0	#DIV/0!		0		0				0	0	#DIV/0!	
Cervix	2	0.00%		0		0				0	2	0.00%	
Descent	2	0.00%		0		0				0	2	0.00%	
Time	1	0.00%		0		0				0	1	0.00%	
Contractions	1	0.00%		0		0				0	1	0.00%	
Pulse	1	0.00%		0		0				0	1	0.00%	
BP	0	#DIV/0!		0		0				0	0	#DIV/0!	
Temp	0	#DIV/0!		0		0				0	0	#DIV/0!	
Resp	0	#DIV/0!		0		0				0	0	#DIV/0!	
Protein	0	#DIV/0!		0		0				0	0	#DIV/0!	
Acetone	0	#DIV/0!		0		0				0	0	#DIV/0!	
Volume	0	#DIV/0!		0		0				0	0	#DIV/0!	
	0	16	0.00%	0	0	0	0			0	16	0.00%	
Summary													
	Marks are there? (possible)		Marks are accura (possible)	Symbols correct? (possible)	Plotted on correc (possible)	Spacing?	(possible)			TOTAL	TOTAL PTS POSSIBLE		
1st Stage	3									0	3		
2nd Stage	4									0	4		
3rd Stage	24									0	24		
(PP Reminder ID)	1									0			
Delivered By:										0	31	0.00%	

(Double click on the Excel Object above to open the partograph grading rubric in Microsoft Excel.)

Grading Rubric Use Instructions:

Enter the IP Number into cell B2.

Enter Date Admitted (MM/DD/YY) into cell G1. To determine date admitted, refer to the admission date recorded in the Patient Information section at the top of the Partograph. If that is not available, refer to the Maternity Record, and then to the admission date indicated Inpatient/Outpatient Record with the first sign of recorded vitals.

Enter Time Admitted (ex. 1p or 1a) into cell G2. To determine time admitted, refer to the admission time recorded in the Patient Information section of the Partograph, or if the Partograph includes a mark at 3 or 4 cm dilation, indicating when active labor began, use the time when these marks were recorded. If these are not available, refer to the Maternity Record, and then to the admission time indicated with the first sign of recorded vitals on the Inpatient/Outpatient Record.

Enter Date Delivered (MM/DD/YY) into cell I1. To determine date delivered, refer to the Summary of Labour at the bottom of the Partograph. If the information is not available in the summary, refer to the case notes.

Enter Time Delivered (ex. 3p or 3a) into cell I2. To determine time delivered, refer to the Summary of Labour at the bottom of the Partograph. If the information is not available in the summary, refer to the case notes.

If you are unable to determine the time and date of admission or delivery, the Partograph cannot be graded.

Once the time and date of admission and delivery have been recorded, the points possible for each category will be calculated.

Enter the number of marks present in the Patient Information section into cell B4. There are always 8 points possible in the Patient Information section. Points are awarded based on the presence of a mark in each category (Name, Age, Gravida, Para, IP Number, Date of Admission, Time of Admission, Ruptured Membranes).

Enter the number of marks present for fetal heart rate into cell B5.

Enter the number of correct symbols for fetal heart rate into cell G5. Only solid dots are considered correct symbols for fetal heart rate.

Enter the number of spacing points earned for fetal heart rate into cell K5. Measurements are taken every half hour, so properly spaced marks should have one box between them.

Enter the number of marks present for liquor into cell B6.

Enter the number of correct symbols for liquor into cell G6. Correct symbols include I, C, M, A or B (Kenya only).

Enter the number of spacing points earned for liquor into cell K6. Measurements are taken every four hours, so there will be three boxes between properly spaced marks.

Enter the number of marks present for moulding into cell B7.

Enter the number of correct symbols for moulding into cell G7. Correct symbols include O, +, ++, and +++.

Enter the number of spacing points earned for moulding into cell K7. Measurements are taken every four hours, so there will be three boxes between properly spaced marks.

The spreadsheet will calculate the number of marks possible for cervical dilation and descent based on the number of four-hour measurements, but some adjustments may need to be made. A complete Partograph for labor resulting in an SVD must include a cervical dilation measurement at 10 cm and a descent of the fetal head measurement at 0, even if these milestones occur less than four hours after the last measurements. If there are marks present equal to the number of four-hour measurements, but no mark present at 10 cm (cervical dilation) or 0 (descent), there should be an additional mark possible. After determining the number of marks possible, enter the number of marks possible for cervical dilation into cell C8 and the number of marks possible for descent into cell C9.

Enter the number of marks present for cervical dilation into cell B8.

Enter the number of correct symbols for cervical dilation into cell G8. The correct symbol is an X.

Enter the number of spacing points earned for cervical dilation into cell K8. Measurements are taken every four hours, so properly spaced measurements should have three boxes between them.

If the final mark at 10 cm is spaced less than four hours from the preceding measurement, a spacing point is still awarded.

Enter the number of marks present for descent into cell B9.

Enter the number of correct symbols for descent into cell G9. The correct symbol is an O.

Enter the number of spacing points earned for descent into cell K9. Measurements are taken every four hours, so properly spaced measurements should have three boxes between them. If the final mark at 0 is spaced less than four hours from the preceding measurement, a spacing point is still awarded.

Enter the number of marks present for time into cell B10.

Enter the number of correct symbols for time into cell G10. Symbols are considered correct if they are legible numbers.

Enter the number of spacing points earned for time into cell K10. Properly spaced marks indicate a one-hour difference between each mark with no spaces in between.

Enter the number of marks present for contractions into cell B11.

Enter the number of correct symbols for contractions into cell G11. Correct symbols include columns shaded with dots (contractions less than 20 seconds in duration), diagonal stripes (20-40 seconds in duration) or solid shading (greater than 40 seconds in duration), Column heights should correspond to the number of contractions occurring in a ten-minute interval.

Enter the number of spacing points earned for contraction into cell K11. Contractions are measured every half hour. There should be no spaces between contractions unless contractions have ceased.

Enter the number of marks present for pulse into cell B12.

Enter the number of correct symbols for pulse into cell G12. Only solid dots are considered correct symbols.

Enter the number of spacing points earned for pulse into cell K12. Pulse is measure every half hour. There will be one box between properly spaced marks.

Enter the number of marks present for blood pressure into cell B13.

Enter the number of correct symbols for blood pressure into cell G13. The correct symbol for blood pressure is a double-headed vertical arrow with the top of the arrow ending at the systolic reading and the bottom point indicating the diastolic reading.

Enter the number of spacing points earned for blood pressure into cell K13. Blood pressure is measured every four hours. There should be three boxes between properly spaced measurements.

Enter the number of marks present for temperature into cell B14.

Enter the number of spacing points earned for temperature into cell K14. Temperature is measured every four hours. There should be three boxes between properly spaced measurements.

Enter the number of marks present for respirations into cell B15.

Enter the number of spacing points earned for respirations into cell K15. Respirations are measured every four hours. There should be three boxes between properly spaced measurements.

Enter the number of marks present for protein into cell B16.

Enter the number of correct symbols for protein into cell G16. Correct symbols for protein indicate the absence or presence of protein in the urine.

Enter the number of spacing points earned for protein into cell K16. Protein is measured every four hours. There should be three boxes between properly spaced measurements.

Enter the number of marks present for acetone into cell B17.

Enter the number of correct symbols for acetone into cell G17. Correct symbols for acetone indicate the absence or presence of acetone in the urine.

Enter the number of spacing points earned for acetone into cell K17. Acetone is measured every four hours. There should be three boxes between properly spaced measurements.

Enter the number of marks present for volume into cell B18.

Enter the number of spacing points earned for volume into cell K18. Volume is measured every four hours. There should be three boxes between properly spaced measurements.

Enter the number of marks present in the 1st Stage of the Summary of Labour into cell B24.

Enter the number of marks possible for the 2nd Stage of the Summary of Labour into cell C25. If drugs were given, there are 4 points possible. If drugs were not given, there are 2 points possible.

Enter the number of marks present in the 2nd Stage of the Summary of Labour into cell B25.

Enter the number of marks present in the 3rd Stage of the Summary of Labour into cell B26.
If a PartoPen reminder ID is noted, enter 1 into cell B27. If not, enter 0 into cell B27.