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Using Clinical Cascades to Measure Facilities' Obstetric Emergency Readiness: An Analysis of Facility Assessments in Migori County, Kenya and Busoga Region, Uganda

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Using Clinical Cascades to Measure Facilities' Obstetric Emergency Readiness: An Analysis of Facility Assessments in Migori County, Kenya and Busoga Region, Uganda

By

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2016

Thesis Committee Chair: Jessica Sales, PhD

An abstract of a thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University in partial fulfillment of the requirements for the degree of Master of Public Health
in Behavioral, Social, and Health Education Sciences
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Abstract

Background: Globally, hundreds of women die each day from preventable causes related to pregnancy and childbirth. Nearly 75% of all maternal deaths are attributable to severe bleeding, infections, high blood pressure, delivery complications, and unsafe abortions. Most deaths can be avoided if deliveries are attended to by skilled professionals who have emergency management skills and strategic emergency supplies. High rates of avoidable deaths persist, especially in Sub-Saharan Africa, despite existing facility readiness estimation and intervention strategies. Therefore, facilities and health systems may benefit from more detailed analysis of emergency readiness than is currently available. This study was designed to: (1) compare estimates of facility readiness to manage common obstetric emergencies using clinical cascades and signal functions, (2) compare the estimates between countries and levels of care in Kenya and Uganda, and (3) test the cascading loss of emergency obstetric resources within the two countries.

Methods: Data from all 23 facility in the Preterm Birth Initiative (PTBi) study were used to create signal function and clinical cascade emergency readiness estimates. Facility data were collected in 2016 from Migori County, Kenya and Busoga Region, Uganda. The cascades measure the proportion of facilities with the resources to identify the emergency (stage 1), treat it (stage 2), and monitor-modify therapy based on clinical response (stage 3). Emergency readiness at the treatment stage was used to evaluate the performance against the signal functions.

Results: Four critical findings emerged from readiness estimates with the cascades. First, the signal functions overestimated practical emergency readiness by 22.61% across the five emergencies. Second, based on both clinical cascade and signal function estimates, not all comprehensive emergency obstetric care facilities were ready to perform basic emergency obstetric care, with an estimated readiness of 58.00% and 80.00%, respectively, across the five emergencies. Third, across all five clinical cascade emergencies, there was a consistent pattern of readiness loss. Less than half (46.96%) of facilities had all the resources necessary to identify and treat the leading causes of maternal death. Fourth, across the three stages of care, there was a consistent pattern of 28.41% readiness loss for all emergencies. Most readiness was lost in the treatment stage (mean of 33.91%); however, this varied by emergency.

Conclusions: These findings support growing consensus on the need to revise standard measures of obstetric emergency readiness. In contrast to the signal functions, the clinical cascades presents a step-wise, emergency-specific estimate of readiness. This novel approach offers a more nuanced picture of facility readiness that can inform facility or health system-level policy or programs. Since accurate measurement of emergency readiness is a prerequisite for strengthening a facility's capacity to manage emergencies, the cascades may provide a more quantifiable, relevant, and actionable assessment that is specific to each emergency. Future testing in varied geographic and health facility level settings is warranted.

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ABBREVIATIONS

AMDD	Averting Maternal Death and Disability
BEmOC	Basic Obstetric Emergency Care
BEmONC	Basic Emergency Obstetric-Neonatal Care
CEmOC	Comprehensive Obstetric Emergency Care
CEmONC	Comprehensive Emergency Obstetric-Neonatal Care
DUA	Data Use Agreement
EmOC	Emergency Obstetric Care
HICs	High Income Countries
IQR	Interquartile Range
IRB	Institutional Review Board
MDGs	Millennium Development Goals
MMR	Maternal Mortality Ratio
MNM	Maternal Near Miss
MNMR	Maternal Near Miss Ratio
PFP	Private-for-Profit
PI	Principal Investigator
PMTCT	Prevention of Mother-to-Child Transmission of HIV
PNFP	Private-Not-for-Profit
PTBi	Preterm Birth Initiative
SAM	Service Availability Mapping
SARA	Service Availability and Readiness Assessment
SARAM	Service Availability and Readiness Assessment Mapping
SD	Standard Deviation
SDGs	Sustainable Development Goals
SMO	Severe Maternal Outcomes
SMOR	Severe Maternal Outcomes Ratio
SPA	Services Provision Assessment
SRI	Service Readiness Index
UCSF	University of California, San Francisco
UN	United Nations
UNFPA	United Nations Population Fund
UNICEF	United Nations Children's Fund
WHO	World Health Organization

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I share credit for this work with all of you.

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CHAPTER 1: INTRODUCTION

Introduction and Rationale

In 2017, more than 800 women died daily from preventable pregnancy and childbirth related causes, totaling nearly 300,000 deaths worldwide throughout the year [1]. The global maternal mortality ratio (MMR) is the number of maternal deaths per 100,000 live births. In 2017, the global ratio was 211 [2]. Moreover, more than 9% of all deaths to women of reproductive age (15-49 years) around the world are due to maternal causes [2].

Reducing maternal mortality has been a top health and development priority for decades, beginning with the 1987 Safe Motherhood Conference in Nairobi, Kenya, and followed by the 1990 United Nations (UN) World Summit for Children, the 1994 International Conference on Population and Development, the 1995 Fourth World Conference on Women, 'Nairobi 10 Years On' in 1997, and the Millennium Development Goals established by the UN in 2000 [3]. The Millennium Development Goals (MDGs) was a series of eight goals centered on reducing extreme poverty globally by 2015. The MDGs included goals on reducing child mortality (MDG 4) and improving maternal health (MDG 5) [3]. In 2015, the UN negotiated the post-2015 development agenda, which led to the creation of the 17 Sustainable Development Goals (SDGs). SDG 3, focused on "good health and well-being," includes a specific target for maternal mortality: By 2030, reduce the global maternal mortality ratio to less than 70 per 100,000 live births [4]. With decades of investment on maternal health and survival, the evidence-base for mortality-reducing interventions in pregnancy has dramatically expanded. Reducing maternal mortality requires a complex interplay of strategies focused on pregnancy, delivery, and the postpartum period. Pregnancy strategies include access to quality prenatal care, complication prevention, and emergency preparedness. Delivery strategies include access to quality delivery care as well as detection and timely management of complications. Postpartum strategies include

quality postpartum care and early detection and management of complications that arise during or after birth [5].

Much progress has been made as a result of the efforts in recent decades, with the global MMR steadily declining from 342 in 2000 to 211 in 2017, a nearly 40% reduction [6]. However, despite global progress, geographic disparities in maternal health outcomes persist. The disproportionately high MMRs seen in certain parts of the world reflect inequities in health care quality and accessibility and persistent gaps in the distribution of social and economic resources [1]. Ninety-four percent of preventable maternal deaths occur in low- and lower-middle-income countries [1]. In 2017, the MMR in low-income countries was 462, 42 times greater than the ratio in high income countries (HICs) (11 per 100,000) [1]. Moreover, a woman's lifetime risk of maternal death (the probability that a 15-year-old woman will eventually die from a maternal cause) is around 120 times higher in low-income countries (1 in 45), compared to high income countries (1 in 5,400) [1]. Eighty-six percent of the total global deaths occur in Sub-Saharan Africa and Southern Asia [1]. Nearly two-thirds of the global burden of maternal mortality comes from Sub-Saharan African countries alone, where the regional MMR is 542 [1,4]. Over the last two decades, the MMR in East African countries steadily declined from 851 in 2000 to 428 in 2017 [4]. Kenya and Uganda, the countries of interest in this data analysis, also reduced their MMRs substantially in the recent decades. Kenya's MMR dropped from 708 to 342 (52% decrease) between 2000 and 2017 and Uganda's MMR fell from 578 to 375 (35% decrease) over the same time period [4].

Nearly 75% of all maternal deaths are attributed to five major complications: severe bleeding (hemorrhage), infections (sepsis), high blood pressure (pre-eclampsia and eclampsia), delivery complications, and unsafe abortions [7]. Most of these maternal deaths can be prevented if deliveries are attended by skilled professionals who have the training, equipment, and supplies necessary to identify and manage the emergency (with triage and referral to outside care as necessary) [7]. Labor complications require quick and easy access to high-quality emergency

obstetric care (EmOC). Basic Emergency Obstetric Care (BEmOC) treats the majority of causes of maternal death. BEmOC requires essential supplies, durable equipment, and targeted drugs. Comprehensive Emergency Obstetric Care (CEmOC) expands on BEmOC and also includes resources for blood transfusion and surgery [7]. Mobilizing and dispensing the clinical resources required to manage basic obstetric emergencies may be a critical step for reducing persistently elevated MMRs in Sub-Saharan African contexts such as Kenya and Uganda. Therefore, accurate measurement of a facility's readiness to manage these emergencies is urgently needed.

In the 1990s, the World Health Organization (WHO) identified the resources necessary to manage common obstetric emergencies [5]. This approach evolved into the "signal functions," six clinical actions (three medical treatments and three manual procedures) used during basic obstetric emergencies. The medical treatments include administering parenteral (1) antibiotics, (2) uterotonic drugs, and (3) anticonvulsant drugs for pre-eclampsia and eclampsia. The manual procedures include (4) manually removing retained placentas, (5) removing retained products of conception, and (6) performing assisted vaginal deliveries [3]. Specific items (tracers) are used as a proxy to measure a facilities' ability to handle obstetric emergencies [3,8-13].

The signal functions are the dominant method for assessing obstetric emergency readiness at facilities worldwide [14-16]. In recent years, however, there is growing consensus on the need to revise and expand this method [9,11,17-22]. One particular weakness is its inability to predict facilities' readiness to manage *specific* emergencies [17,19]. Also, the signal functions do not adequately account for the resources required to first *identify* the disorder or the consumable supplies and durable goods required to deliver the treatment or perform the procedure [22]. Therefore, to make progress on reducing delivery-related mortality, we need a more robust set of measurable indicators that are emergency/outcome-specific and relevant for multiple levels of the health system [22].

Building off the signal functions model, the clinical cascade model is a clinically-oriented approach to measuring facility readiness using a step-wise cascading relationship between

emergency resources [22-24]. The cascade model defines emergency readiness as the proportion of facilities that can *identify* an emergency and have the resources (including drugs, supplies, and equipment) to *treat* the identified emergency. The ability to *monitor and modify* the initial treatment as clinically indicated is a measure of quality care [22].

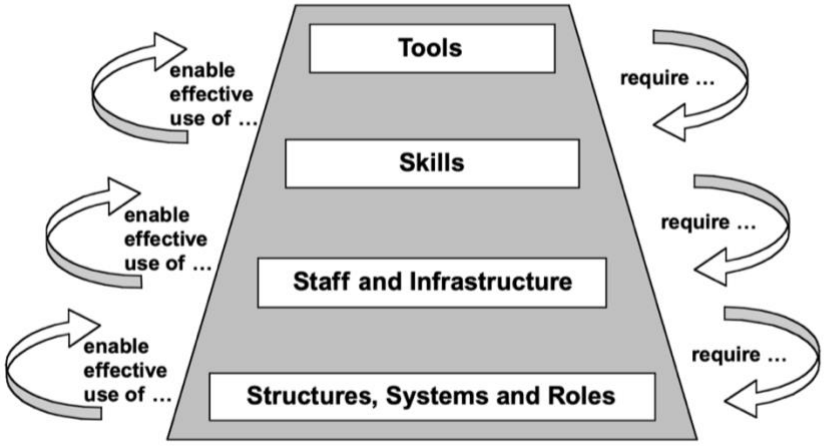
Unlike the wealth of research on signal functions as a measurement of facilities' readiness to handle obstetric emergencies, the clinical cascades have been tested in only a handful of locations. Moreover, to date, only one published study compares the two methods in the context of facilities' readiness to manage maternal and infant health emergencies. As an emerging metric, there are limited studies comparing the clinical cascades and signal functions as methods to assess facilities' readiness to handle basic obstetric emergencies. Further, there are very few studies that link either metric (cascades and signal functions) to adverse clinical outcomes (e.g., mortality as measured by MMR, maternal near miss (MNM), as measured by Maternal Near Miss Ratio (MNMR), or severe maternal outcomes (SMO), as measured by Several Maternal Outcomes Ratio, SMOR) [22,25-32].

Problem Statement

Emergency obstetric care is critical in managing the obstetric complications driving elevated maternal mortality ratios in Sub-Saharan Africa. However, measuring individual facility or health system capacity to provide such care remains challenging. Though the signal functions model has been the dominant method of measurement to date, growing research suggests critical weaknesses in this method. The novel clinical cascades method is proposed as a clinically-relevant approach for measuring both individual clinic and broader health system readiness. With a few additional indicators compared to the signal functions, it more comprehensively provides measures of readiness by emergency and step of clinical care. Like the signal functions, however, it has not been used to predict clinical outcomes. Testing the cascades and their estimates of readiness as compared to the signal functions in a variety of countries and contexts requires additional research.

Theoretical Frameworks

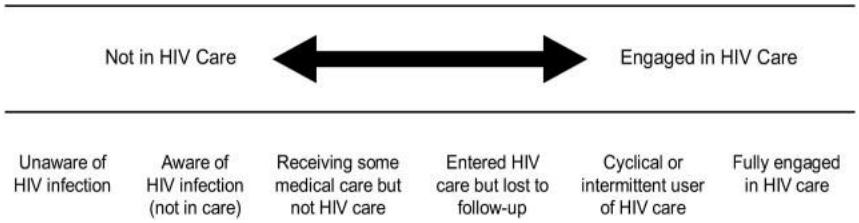
Systemic Capacity Building and Spectrum of Engagement in HIV Care were guiding frameworks used in the original development of the clinical cascade model and, therefore, this study. Christopher Potter and Richard Brough developed the Systemic Capacity Building framework in the context of exploring why staff in the Indian health and family welfare system failed to provide effective services [23]. This formative framework has been widely cited and adapted in health research. Responding to the vague calls for "capacity building" in international development, Potter and Brough instead proposed four stages in the progressive hierarchy of developing "capacity." These stages include capacity in 1) Structures-Systems-Roles, 2) Staff-Infrastructure, 3) Skills, and 4) Tools (Figure 1) [23]. The inputs required to build 'capacity' vary widely across each of these four stages. For example, introducing a technological solution (4) without first creating skill for using the tool (3) would result in limited use of the new tool [23]. Applying this hierarchy of needs framework to a health system can aid in identifying the gaps in each of the four stages of capacity and help to target inputs for improving specific capacities. This enables interventions to be more targeted and strategic [23]. The predictable, interdependent relationship between structures, systems and roles, staff and facilities, skills, and tools, as outlined in Potter and Brough's framework is reflected in the clinical cascades [22]. Clinical tools, such as lifesaving obstetric medication, can only be effective if facility staff possess the knowledge and skills to diagnose the disorder, followed by the equipment to administer treatment drugs [22].



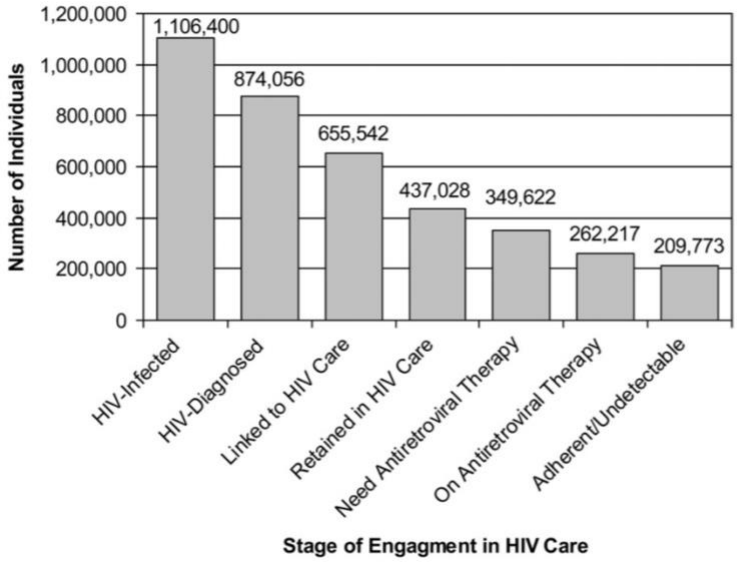
Potter and Brough's Systemic Capacity Building Framework: Capacity Pyramid [23]

The Spectrum of Engagement framework was originally applied to HIV care to describe the full continuum of HIV care and patients' engagement in such care [24,33]. It illustrates a nuanced trajectory of care from initial diagnosis to sustained treatment with HIV-suppressing medications (Figure 2). Thus, successful treatment of a patient's HIV and prevention of further virus spread, requires multiple steps such as testing, retaining, and treating patients. Any failure to move from one step (e.g., testing) to the next step (e.g., notification of test result) breaks the continuum of care and results in an untreated patient. The predictable cascade of patient loss demonstrated in the context of HIV care (Figure 3) has also been applied to other areas of medicine, such as hepatitis and, more recently, obstetrics [22,34]. The clinical cascade model used in this study relies on the underlying principles of the Spectrum of Engagement in HIV Care framework – successful management of obstetric emergencies requires that facilities have the proper tools and staff skill to (1) diagnose the complication, (2) treat the complication, and (3) monitor and modify treatment as appropriate. Disruption in the first stage (diagnosis) will inhibit the subsequent

stages of care. Similarly, gaps in providing treatment inhibit subsequent monitoring and the emergency's progression.



Health Resources and Services Administration (HRSA) Continuum of HIV Care [24]



Drop-Off in Engagement along the Spectrum of HIV Care [24]

Purpose Statement

Detailed analysis of a facility's readiness to handle obstetric emergencies may be used to guide emergency-specific or supply-specific interventions to close gaps in emergency supplies. Real-time or demand-based requests for strategic emergency supplies may close gaps in supply availability and strengthen systems' capacity to successfully manage labor-related emergencies at individual facilities or across health system networks. Building off of the wealth of research on the signal functions and the formative research on clinical cascades, this study was designed to

assess emergency readiness by comparing the signal functions to the novel clinical cascade approach at BEmOC-providing facilities in two East African countries. More specifically, this study aimed to: (1) compare estimates of facility readiness to manage common obstetric emergencies using clinical cascades and signal functions, (2) compare the estimates between countries and levels of care in Kenya and Uganda, and (3) test the cascading loss of emergency obstetric resources within the two countries.

Research Questions

This study was designed to answer the following research question and sub-questions:

1. How prepared are participating facilities in Kenya and Uganda to manage obstetric emergencies as measured by the clinical cascades?
    a. How does the level of preparedness as measured by the clinical cascades compare to that measured by the signal functions?
    b. Are there co-factors that predict emergency readiness across facilities (e.g., country, facility ownership, or level of care)

The limited available published research suggested that the signal functions would estimate a higher level of preparedness than that estimated by the clinical cascades and that overall estimates of readiness would be higher among higher-level facilities [22,25]. Previous research had not explored the role of setting (as measured by country) or facility ownership in readiness estimates.

Significance Statement

This study was designed to inform strategies that optimize emergency commodity provision at Kenyan and Ugandan facilities, strengthen system-level strategies for maternal survival, and expand global scholarship on measuring obstetric emergency readiness at facilities and in health systems using the novel cascade metrics.

This study sits within broader maternal and child health initiatives underway at both Emory University and the University of California, San Francisco (UCSF). This cross-institutional team is implementing and evaluating packages of facility-based interventions to improve maternal and neonatal care. In Eastern Uganda and Western Kenya, specifically, researchers are evaluating a four-component intervention that involves: (1) strengthening of routine data collection and data use activities; (2) implementation of the WHO Safe Childbirth Checklist, adapted for preterm birth; (3) PRONTO simulation training and mentoring to strengthen intrapartum and newborn care; and (4) support of quality improvement teams [35,36]. This study built off of the team's formative research on a community-facility intervention package for reducing maternal mortality in Western Kenya and the forthcoming Survive-Thrive study on emergency readiness in Amhara, Ethiopia. In collaboration with the ongoing work of Emory and UCSF, the results of this study can inform health systems transformation to improve maternal survival—particularly in East Africa.

Definition of Terms

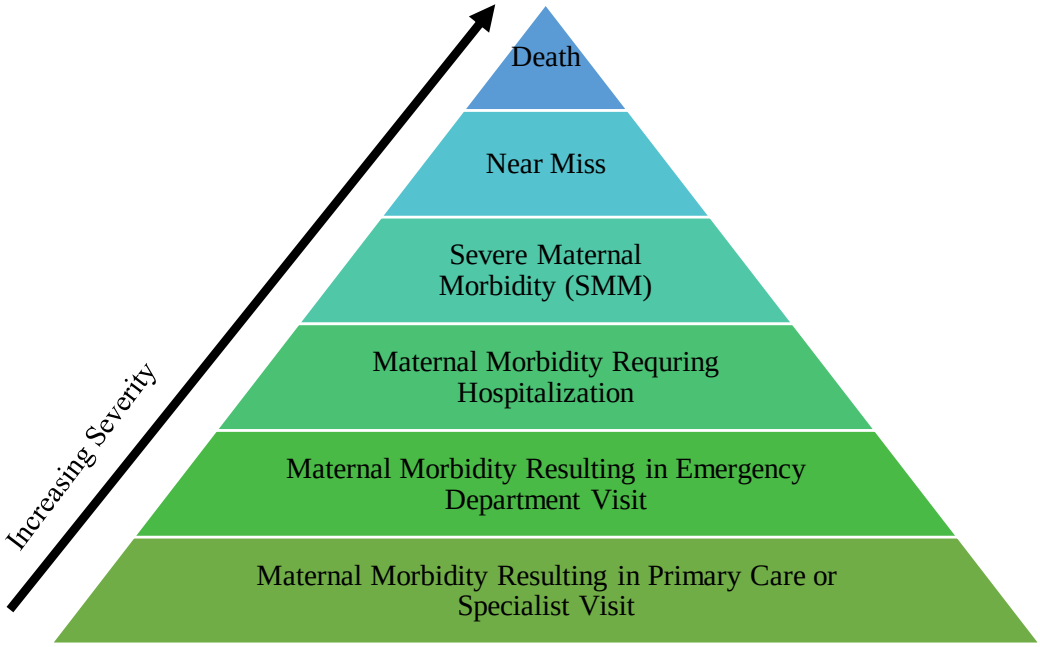
- **Maternal deaths:** The death of a woman during pregnancy or within 42 days of termination of the pregnancy, regardless of the duration and site of the pregnancy, from any cause related to or exacerbated by the pregnancy or its management, excluding accidental or incidental causes [37]
- **Live birth:** the complete expulsion or extraction of a product of conception from its mother, irrespective of pregnancy duration, which, after separation, breathes or shows other signs of life [37]
- **Maternal Mortality Ratio (MMR):** Maternal deaths per 100,000 live births [37]
- **Hemorrhage:** Severe bleeding before (antepartum hemorrhage) or after (postpartum hemorrhage) labor [3]

- **Sepsis:** A complication caused by infection, resulting in high temperatures (38° C or higher) and one or more of the following symptoms: lower abdominal pain, abnormal vaginal discharge, and tender or poorly contracted uterus [3]
- **Preeclampsia:** A sudden spike in maternal blood pressure accompanied by protein in the urine, which can progress to a more serious eclampsia [3]
- **Eclampsia:** A blood-pressure related disorder that can result in maternal seizures which, untreated, can progress to coma or death [3]
- **Prolonged or obstructed labor:** Occurs when the first stage of labor lasts longer than 12 hours, the second stage of labor lasts longer than one hour, or labor is obstructed by uterine scarring or fetal malpresentation (fetus side (transverse), brow, or face presenting in the uterine isthmus instead of the head) [3].
- **Abortion:** The termination of a pregnancy through the removal of pregnancy tissue, products of conception, or the fetus and placenta from the uterus [38]. Complications of a spontaneous or induced abortion, especially an induced abortion performed in non-medical/unsterile settings, which can result in hemorrhage, sepsis, or other complications [3]
- **Emergency Obstetric Care (EmOC):** Clinical processes needed to rapidly manage or stabilize a patient whose life is in imminent danger during pregnancy [18]
- **Basic Emergency Obstetric Care (BEmOC):** Defined as the ability to perform six maternal signal functions: (1) administer parenteral antibiotics, (2) administer uterotonic drugs, (3) administer parenteral anticonvulsants for pre-eclampsia and eclampsia, (4) manually remove the placenta, (5) remove retained products of conception, and (6) perform assisted vaginal delivery [3]
- **Comprehensive Emergency Obstetric Care (CEmOC):** Defined as the ability to perform the six basic signal functions as well as surgery and blood transfusion [3]

- **Signal functions:** Six clinical actions, three medical and three manual procedures, used during obstetric emergencies [3]
- **Clinical cascades:** A clinically-oriented approach to measuring facility readiness using a step-wise cascading relationship between emergency resources [22,25]

CHAPTER 2: LITERATURE REVIEW

Pregnancy outcomes can be classified on a continuum of severity from normal/healthy pregnancy to 'maternal near misses (MNM),' morbidity (disability), severe morbidity, and death (Figure 4) [26]. On the most severe end of the pregnancy outcome continuum lies maternal mortality, an outcome that continues to plague countries across the globe today. In 2017, more than 800 women died daily from preventable pregnancy and childbirth related causes, totaling nearly 300,000 deaths worldwide throughout the year [1].



Continuum of Maternal Morbidity [39]

Nearly 75% of all maternal deaths are attributed to five major complications: hemorrhage, sepsis, preeclampsia/eclampsia, prolonged or obstructed labor, and complications from unsafe abortions [7]. Hemorrhage refers to severe bleeding before (antepartum hemorrhage) or after (postpartum hemorrhage) labor [3]. The severity of hemorrhage is related to the amount of blood loss and delivery type. It can be categorized as mild, moderate, and severe [3]. Sepsis is caused by an infection in the blood stream with systemic symptoms [3]. Syndromically, it is

characterized by high temperatures (38°C or higher) and one or more of the following: lower abdominal pain, abnormal vaginal discharge, tender or poorly contracted uterus [3]. It can be lab-confirmed with blood cultures in facilities where testing is available [3]. Preeclampsia and eclampsia are blood-pressure related disorders that can include symptoms of headache, hyperreflexia (overactive or overresponsive reflexes), blurred vision, oliguria (low urine output), epigastric (upper abdominal) pain, pulmonary edema (fluid in the lungs), and convulsions (seizures) [3]. Pre-eclampsia refers to a sudden spike in maternal blood pressure with detectable protein in the urine [3]. When undetected and untreated, pre-eclampsia progresses to eclampsia, a disorder marked by seizures and loss of consciousness as a result of high blood pressure [3]. Coma and death follow severe, untreated eclampsia. Prolonged or obstructed labor occurs when the first stage of labor lasts longer than 12 hours, the second stage of labor lasts longer than one hour, or labor is obstructed by uterine scarring or fetal malpresentation (fetus side (transverse), brow, or face presenting in the uterine isthmus instead of the head) [3]. Lastly, complications of a spontaneous or induced abortion can result in hemorrhage or sepsis [3]. The majority of all maternal deaths occur around labor, delivery, and within the first 24 hours postpartum. Consequently, health facilities caring for laboring mothers can play a critical and substantive role in addressing these five primary drivers and preventing death around the time of birth [40].

Pregnancy-related deaths result not only in mothers' suffering, but also have serious implications for the health and well-being of newborns, families, and communities at large. A study in Western Kenya found that of the 90 live babies born to women who died from pregnancy or labor-related causes between 2003 and 2011, 25% died within one week of birth [41]. By one year, more than two-thirds of the infants had died [41]. By comparison, babies born to mothers who lived had much greater survival. Nearly all (99%) of these infants survived their first week (versus 75%) and nearly all infants remained alive at one year (versus 33%) [41]. As such, reducing maternal mortality not only saves mothers' lives, but also protects the health of their infants. Moreover, maternal deaths can result in persistent social and economic losses. As

described in the WHO's landmark *Mother-Baby Package: Implementing Safe Motherhood in Countries*, "The women who die are in the prime of life, responsible for the health and well-being of their families. They generate income, grow and prepare food, educate the young, care for children, the elderly, and the sick. Their deaths represent a drain on all development efforts." [5] Further, older children of deceased mothers are more often forced to withdraw from school due to financial strains or increased household or childcare responsibilities [41]. The trauma of a mother's death may also cause familial breakdown, as extended families stop gathering for meals together or children go to live with other relatives [41]. Preventing maternal mortality is, therefore, fundamental to the health and well-being of women, children, families, and societies at large.

Maternal Mortality in Kenya and Uganda

Targeted interventions to reduce maternal mortality and prevent these long-term impacts, are especially important in high-risk areas of the world. Maternal deaths are not evenly distributed across the globe, with Sub-Saharan African countries alone accounting for nearly two-thirds of preventable maternal deaths [2]. The MMRs in Kenya and Uganda, the countries of interest for this study, declined substantially over the last two decades (reductions of 52% and 35%, respectively), but remain more than 30 times the MMRs found in high-income countries.

Kenya is an East African country bordered by Ethiopia, Sudan, Uganda, the United Republic of Tanzania, Somalia, and the Indian Ocean. Within its 47 administrative counties and 290 sub-counties, Kenya is home to 52.6 million people [15,42]. As of 2017, Kenya had an MMR of 342 [4]. Kenya's MMR was well below both the Sub-Saharan (542) and East African (428) ratios [4]. Yet, it was 62% higher than the global ratio of 211 [4]. Sitting to the east of Kenya, and also bordered by Tanzania, Rwanda, the Democratic Republic of the Congo (DRC), and South Sudan, Uganda is home to more than 44 million residents [43]. Uganda's 2017 MMR of 375 was only slightly higher than Kenya's yet markedly higher than the global MMR (211) [4,44].

Emergency Obstetric Care

Pregnancy trajectories can be unpredictable. The life-threatening complications driving maternal mortality can arise quickly and without warning in previously healthy pregnancies. For this reason, Emergency Obstetric Care (EmOC) has been dubbed the "keystone in the arch of safe motherhood" [40]. EmOC includes clinical care needed to rapidly manage or stabilize a patient whose life is in imminent danger [18]. There are two primary forms of EmOC, Basic Emergency Obstetric Care (BEmOC) and Comprehensive Emergency Obstetric Care (CEmOC). Labor complications require quick and easy access to high-quality EmOC, including lifesaving drugs, supplies, and equipment. In the absence of these medical interventions, labor complications (such as the five leading causes of maternal mortality) can progress quickly and with devastating effects. For instance, without treatment, a ruptured uterus (a potential complication of unsafe abortions) can cause death within 24 hours of onset, antepartum hemorrhage can cause death within 12 hours, and postpartum hemorrhage can cause death within as little as two hours [3]. In addition to providing life-saving clinical interventions, EmOC includes prompt provision of referral to higher levels of care, when clinically indicated [18]. Health centers may be capable of handling many common emergencies (such as post-partum hemorrhage) using BEmOC [3]. For other complications, such as severe obstructed labor or circulatory collapse from post-partum hemorrhage, higher-level interventions with CEmOC (e.g. blood transfusions and surgery) are required [3]. Even in rare instances where an emergency requires a higher level of care than can be provided at BEmOC facilities, "first aid" performed at these facilities (e.g., first doses of antibiotics, oxytocin, or IV fluids) can save the patient's life as they await transportation to a CEmOC facility [3]. WHO estimates that 88-98% of maternal deaths can be prevented with timely access to EmOC interventions [40]. With mobilizing and dispensing clinical resources for obstetric emergencies a critical step in reducing the high MMRs in Sub-Saharan Africa, we need an accurate measurement of facilities' readiness to handle such emergencies.

Measuring Emergency Obstetric Care

Accurate information on the allocation and quality of health services is necessary for managing emergencies at the health systems level, monitoring care, and evaluating impact [45]. Growing demand for accountability and positive clinical outcomes requires a systematic way to assess and monitor availability and readiness of life-saving, high-quality emergency obstetric care—including BEmOC [45]. To achieve the SDGs and reduce global maternal mortality, especially in areas with the highest burden (i.e. Sub-Saharan Africa), countries may benefit from stronger metrics for monitoring the readiness of their facilities to deliver lifesaving interventions [45].

The Service Availability and Readiness Assessment (SARA)

The Service Availability and Readiness Assessment (SARA) builds on previous metrics for assessing a health facility's readiness to deliver specified services (including emergency obstetric care, HIV management, and many other clinical services) [45]. The Service Availability Mapping (SAM) tool was deployed by the WHO and used in the early 2000s to measure service readiness. The Services Provision Assessment (SPA) tool, developed by ICF International in 1997, is still used to measure obstetric emergency readiness [45]. The SARA builds off of these tools and focuses on three main areas: service availability, general service readiness, and service-specific readiness [45]. Service availability refers to the physical presence of services, incorporating health infrastructure, key personnel, and aspects of service utilization. It does not include more complex factors such as geographical barriers, travel time, and user behavior [45]. Some indicators used in SARA for service availability include the density of facilities per population, and the number of inpatient beds, maternity beds, core health workers, outpatient visits, and inpatient admissions [46]. The second SARA component is general service readiness. This refers to the overall capacity of facilities to provide general health services. It includes indicators for five key areas: basic amenities, basic equipment, standard precautions for infection prevention,

diagnostic capacity, and essential medicines [45]. Thirdly, SARA's service-specific readiness refers to health facilities' ability to provide specific health services as measured by the availability of service-specific items in four domains: staff and training, equipment, diagnostics, and medicines-commodities [45]. Service-specific readiness areas include family planning, antenatal care, obstetric care, neonatal care, child health, infectious diseases, and chronic disease [46].

Signal Functions

To measure obstetric services, the WHO developed the obstetric-specific Service Readiness Index (SRI) within SARA. The obstetric-specific index defines a facility's obstetric emergency readiness using a short list of clearly defined "signal functions." There are three medical signal functions (administer parenteral antibiotics, anticonvulsants, and oxytocics) and three manual procedure signal functions (assisted vaginal delivery, removal of retained products of conception, and removal of retained placenta). Facilities that provide these six signal functions are defined as BEmOC facilities. The basic signal functions (BEmOC) do not include every clinical service required to treat pregnancy complications. Rather they serve as an *indicator* of the level of obstetric care provided in a facility [3,47]. In 2006, an international panel of experts advised on a revision to the original signal functions, and in 2009, the WHO, the United Nations Children's Fund (UNICEF), the United Nations Population Fund (UNFPA), and Columbia's Averting Maternal Death and Disability (AMDD) published the revisions in the *Monitoring Emergency Obstetric Care handbook* [3]. The revised basic emergency guidelines for obstetrics and neonatal care (BEmONC) added one signal function for newborn care—basic neonatal resuscitation— in order to provide 7 total signal functions. By extension, comprehensive emergency obstetric-neonatal care (CEmONC) was revised to include functions 1-7 with the addition of surgery (caesarean section) and blood transfusion [3].

Measuring facilities' capacity to perform signal functions can be conducted in several different ways which vary in complexity. Asking staff what signal functions their facility is capable of performing represents the simplest approach [11]. A more sophisticated method is confirming the presence of items needed to perform the signal functions. Specific items (tracers) map to signal functions as proxy measures for a facility's ability to handle the specific obstetric emergencies [3,8-13]. The SRI incorporates this tracer methodology and defines a facility's overall obstetric emergency readiness using the average number of 11 tracers present on the day of observation at the facility [16,45]. Evaluating provider knowledge and determining whether a signal function has actually been performed in the previous months can further improve the precision and validity of emergency management readiness estimates [11]. Perhaps the most sophisticated method involves establishing whether a signal function was performed when needed; however, gathering the data needed to establish the numerator and denominator for this measurement can prove difficult—particularly for routine monitoring in health systems [11]. These three measurement techniques have been applied in the scientific and practice literature to varying degrees.

A wealth of research on signal functions as a measurement of facilities' readiness to handle obstetric emergencies exists. Studies measuring facilities' capacity to perform, or actual performance of, the signal functions found variable results across signal functions, level of facility, and geographic location. A study on the global patterns in availability of EmOC in 24 countries found that while CEmOC facilities were generally widely enough available to meet the recommended minimum number suggested for the population size, there were insufficient numbers and distribution of BEmOC facilities globally [48]. Both BEmOC and CEmOC facilities were concentrated in urban areas, leaving large access gaps in rural areas [48]. Among existing global EmOC facilities, the most frequently performed signal functions were administration of parenteral antibiotics and administration of uterotonic drugs [19,48-56]. In contrast, the least frequently performed were administration of parenteral anticonvulsants and assisted vaginal

delivery [19,48-56]. Beyond limited numbers of some obstetric emergencies presenting for care, lack of critical supplies was frequently cited as a barrier to performing specified signal functions. As the breadth of available studies on signal functions demonstrates, the signal functions continue to be the dominant method to assess emergency readiness at facilities worldwide [14-16]. In recent years, however, consensus on the need to revise this method has grown [9,11,17-22].

One particular weakness of the signal functions model is its inability to predict facilities' readiness to manage *specific* emergencies in their *entirety* [17,19]. The signal functions do not adequately account for the resources required to first *identify* the disorder or the consumable supplies and durable goods required to deliver the treatment or perform the procedure [22]. For example, "administer uterotonic drugs" in the signal function framework fails to account for the refrigeration necessary to maintain the integrity of the oxytocics or the supplies required to administer the drug [22]. Likewise, the signal function estimates group IV tubing, IV catheter, and IV solution as one solitary item, instead of viewing them as discrete, independent items that must all be available in order to perform the function [22]. Given these weaknesses, making progress on reducing delivery-related mortality demands a more robust set of measurable indicators that are emergency/outcome-specific and relevant for multiple levels of health systems in the contexts that bear the brunt of maternal mortality.

Clinical Cascades

Accounting for the weaknesses of the signal functions and building off of the systematic capacity of hierarchy of needs model, the clinical cascade model recently emerged as an alternative approach to measuring facilities' capacity to manage obstetric emergencies; this empiric model is based on the Systemic Capacity Hierarchy of Needs and Spectrum of Engagement frameworks [23,24]. In the capacity hierarchy model, Potter and Brough proposed that the essential components of a functioning health care system fall into a hierarchy, with foundational components such as structures, systems, and roles, required before clinicians can

perform specific tasks (skill) or use specific tools [23]. This model suggests that lifesaving medical interventions can only be performed effectively if the necessary infrastructure, staff, and tools are all first in place. Identifying the specific resources missing at foundational levels of the hierarchy (e.g., clinical staff) can promote improved performance and resource utilization at higher levels (e.g. correct tool use). This framework of systems improvement has been applied to specific health care services to identify resource gaps and prioritize interventions. Care cascades have also been effectively used to analyze health service delivery and identify gaps in care. Pioneering work on the HIV treatment cascade identified patient loss to follow-up at each step of HIV care from initial diagnosis to sustained treatment [24,33,57]. By concretely measuring resource loss at each stage of care, interventions could be designed to better retain patients at critical steps of the care cascade and ultimately improve HIV care and disease management. Since the initial development of HIV care cascades, the approach has been applied to other areas of health care such as prevention of mother-to-child transmission of HIV (PMTCT), hepatitis C, diabetes, hypertension, and, most recently, basic emergency obstetric and neonatal care [22,25,34,58-60].

Building off the signal functions, the capacity hierarchy of needs, and the spectrum of engagement, the clinical cascade model is a clinically-oriented approach to measuring facility readiness using a step-wise cascading relationship between the resources needed to first identify and then manage emergencies [22-24]. The model also explicitly identifies the consumable supplies and durable goods required to deliver life-saving, essential drugs during emergencies [22]. According to the clinical cascade model, emergency readiness is defined as the proportion of facilities that can *identify* an emergency and have the resources to *treat* it. The ability to *monitor and modify* treatment as clinically indicated is considered one indicator of clinical quality [22].[1] The authors of the cascade model suggest that the cascades provide a targeted approach to

[1] As the signal functions to do not measure care quality, specifically, the third stage of the clinical cascades is not used in comparison studies.

measuring readiness for specific emergencies and more accurately estimate practical clinical readiness compared to the signal functions [22].

The clinical cascades have been tested in a handful of countries [22,25]. Formative research conducted in Kenya found that across the five maternal emergencies driving maternal mortality, the signal functions overestimated actual emergency management readiness by 55% [22]. Moreover, a consistent readiness loss of 33% across all cascades (i.e., emergency conditions) and stages of care (identify, treat, monitor/modify) emerged [22]. Across facilities, 39-100% had the resources necessary for identification, 7-57% for treatment, and 0-2% for monitoring or modifying treatment [22]. Similarly, a study examining the clinical cascades as applied to the care of small and sick neonates in Kenya and Uganda found that across all cascades and stages, there was an increasingly consistent pattern of 30-32% overall readiness loss [25]. The study also found mean readiness of 51% for identification, 20% for treatment, and 9% for monitor/modify across six clinical cascades [25]. Findings such as these warrant further research to compare the cascade modeling methods of obstetric readiness in additional global health system contexts.

Emergency Obstetric Care in Kenya and Uganda

Kenya

The Kenyan healthcare system is divided into four levels: community, primary care, county, and national. The community level, "the foundation of the service delivery system," mainly incorporates health promotion activities that are most effectively delivered at the local level [15]. At the primary care level, "the first physical level of the health system," dispensaries, health centers, and maternity/nursing homes offer basic health services to clients [15]. The first level of hospitals, the county level, complements the primary care level, but offers a more expansive package of services [15]. Finally, the national level, comprised of tertiary hospitals,

offers a complete range of services, including highly specialized care [15]. Typically, basic emergency obstetric care is provided at the primary care level and above.

In 2013, the Kenyan Ministry of Health published results from the national Service Availability and Readiness Assessment Mapping (SARAM) [15]. This report provided an overview of health services and their capacity and readiness to provide care across the country. As part of the assessment, data collectors visited 8,401 facilities across the country and collected data on the availability of products related to general medicines, non-communicable diseases, malaria, tuberculosis, HIV, lifesaving commodities, maternal health, vaccines, and children's essential medicines [15]. At both the primary health care and hospital levels, health products for maternal health were least available. For example, 24% of primary care facilities and 29% of hospitals had the products necessary for maternal health care [15]. By comparison, the most available products, vaccine products, were present at 85% of primary care facilities and 80% of hospitals [15]. More specifically, 28% of facilities stocked all essential obstetric medications. This ranged from 18% (in Elgeyo-Marakwet) to 39% (in Muranga) across Kenya's 47 administrative counties [15]. Of the signal function tracer items, 26% of facilities stocked magnesium sulphate (for eclampsia) while up to 53% had gentamicin (an IV antibiotic for sepsis) [15]. The assessment also examined facilities' ability to provide expected services, as defined by the availability of basic amenities, standard precautions, obstetric tracer equipment, and essential obstetric medications [15]. In the realm of maternal health services, slightly over one-fourth (32%) of facilities were ready to provide maternal health services [15]. This service readiness ranged from 56% at hospitals, to 43% at health centers, and 28% at dispensaries, medical clinics, and stand-alone voluntary counselling and testing facilities [15].

Migori County, the specific region where data for the present secondary analysis was originally collected, is located in western Kenya and has a total population of 1.1 million (around 2% of the nation's total population) [61]. In 2013, an estimated 41,547 deliveries took place in the county, with two obstetrician/gynecologists and 66 midwives staffing the facilities in the area

[15]. The 2013 SARAM results found that, of the 169 facilities assessed in Migori, 32% stocked all 11 essential obstetric medications and 38% of facilities were classified as ready to provide maternal health services [15]. With availability and readiness levels in line with the national average, a more in-depth study of Migori facilities' readiness to handle obstetric emergencies could prove meaningful for the country at large.

Uganda

In Uganda, both the public sector (government) and private entities, including private-not-for-profit (PNFP) and private-for-profit (PFP) organizations deliver health care services in the country [62]. The public health sector comprises more than half (55%) of the total health care facilities in Uganda, while PNFPs make up 16% and 29% come from PFPs [62]. At the highest level of the public health care system are national referral hospitals, followed by regional referral hospitals, district health services, general hospitals, and primary care facilities [62]. Primary care includes three levels of facilities: level II (lower-level primary care), III (mid-level primary care), and IV (higher-level primary care) [62]. In terms of obstetric care, hospitals and level IV health centers are expected to provide CEmOC, while level III health centers are focused on basic maternity care and some basic emergency care, and level II facilities mainly provide antenatal and postpartum care [63].

A similar assessment of health services to the one conducted in Kenya was also completed in Uganda. The 2014 Ugandan SARA assessed 152 hospitals and 193 level IV primary care facilities across the country [62]. Nearly all (98%) of the hospitals and health center IVs that were expected to offer delivery services offered them. However, none (0%) had all 67 items used to assess readiness for delivery services [62]. On average, 58% of the items were present in facilities [62]. The most commonly available items were for general clinical care—and were not specific to obstetric emergencies. For example, the most common was the presence of trained staff to support delivery services 24 hours a day, 7 days a week (99%), followed by delivery beds

(98%), sharps container (97%), and disposable latex gloves (97%) [62]. National guidelines for BEmOC (7%), betamethasone (13%), pulse oximeter (13%), and forceps (17%) were among the least available items [62]. The assessment also examined the capacity to offer delivery services, defined by the presence of the 67 items, as well as items needed to administer emergency parenteral drugs (antibiotics, oxytocin, and anticonvulsants), perform procedures (assisted vaginal delivery, removal of the placenta, removal of retained products of conception), and resuscitate neonates [62]. Based on these criteria, only 5% of facilities were deemed to have "very good" obstetric capacity (44% good, 46% moderate, 4% poor, and 0% very poor) [62]. In terms of the discrete tracer items for the six signal functions, between 41-99% of facilities had signal function capacity. Forty-one percent had the tracers for assisted vaginal delivery, 87% for anticonvulsants, 94% for removal of retained products of conception, 96% for placenta removal, 99% for oxytocin, and 100% for parenteral administration of antibiotics [62].

The Busoga region of Uganda, the particular region of interest for this study, is located in East Central Uganda and houses around 10% of the nation's population (around 4,000,000 people) [64]. Though region-specific results were not presented in the 2014 Ugandan SARA, a report based on the 2014 National Population and Housing Census presented some contextual maternal health findings for the region [65]. Busoga has an MMR of 379 per 100,000 live births [65]. Moreover, 17.2% of female deaths in the region are maternal and the lifetime risk of maternal death is 2.6 per 100 women [65]. Though these markers provide a picture of maternal health in Busoga, a more nuanced assessment of the region's readiness to provide emergency obstetric services would prove useful in understanding the current state of health care and designing targeted interventions for improvement for a substantive portion of the country's population. As with Kenya, the findings from the literature on Uganda, and the Busoga region, specifically, warrant additional, detailed study on the state of life-saving emergency obstetric care—particularly since the national MMR remains elevated. A comparison of signal function

and clinical cascade estimates of facilities' readiness to handle obstetric emergencies in Migori County, Kenya, and the Busoga region of Uganda, could fill this need.

Summary

Current literature suggests that emergency obstetric care is essential in managing obstetric complications and preventing maternal mortality. However, measuring facilities' readiness to provide such care remains challenging—particularly for emergency-specific estimates and assessment at population scale. Specifically, there is limited research on the performance of this metric across diverse geographic and facility-level contexts. This study explored facility readiness to manage obstetric emergencies as estimated by both the clinical cascades and signal functions among participating facilities in Kenya and Uganda. Given the importance of emergency obstetric care in reducing global maternal mortality, this comparative analysis of the performance of clinical cascades and signal functions for measuring facility- and health system emergency readiness was timely. It may inform strategies that optimize emergency commodity provision for Kenyan and Ugandan facilities and strengthen system-level strategies for emergency-specific maternal survival. If, as predicted, clinical cascade estimates of readiness indicated lower levels of readiness than determined by the signal functions, it means that fewer facilities in Kenya and Uganda are prepared to handle obstetric emergencies. Findings such as these should serve as a call to action to improve the availability of lifesaving supplies at the studied facilities. This study also expanded global scholarship on measuring obstetric emergency readiness using a clinically-relevant metric. Given the comprehensiveness of the cascade system of measurement, and the preference to under- versus over-estimate readiness, it would then be best to use clinical cascade estimates to guide strategies for strengthening capacity for care. As such, the findings of this study could contribute to the emerging evidence that suggests clinical practice shift away from the signal functions.

CHAPTER 3: STUDENT CONTRIBUTION

Research Question Development

Key study procedures, such as project administration, were undertaken by Bridget Whaley, the MPH student and Principal Investigator (PI) of the study, with support from committee members (Dr. John Cranmer, Dr. Jessica Sales). This study was initially formulated through collaborative discussion with Dr. Cranmer, Assistant Clinical Professor, Emory University's Nell Hodgson Woodruff School of Nursing. Early conversations around study planning also included original study members from the University of California, San Francisco (Dr. Dilys Walker and Ms. Elizabeth Butrick), the Kenya Medical Research Institute (Dr. Anthony Wanyoro), and Makerere University (Dr. Peter Waiswa). The indicators in the UCSF study this thesis was based on were derived from Dr. Cranmer's cascade model and applied to Dr. Walker's prospective facility inventories in the Preterm Birth Initiative (PTBi) study.

Primary Data Collection

UCSF collected the data used in this study in 2016-2019, as part of a pair-matched, cluster randomized controlled trial evaluating a package of facility-based interventions to improve care for preterm infants [35,36]. The variables on emergency obstetric supplies were embedded in PTBi facility inventories based on Dr. Cranmer's collaboration with the PTBi investigator. Twenty[2] health facilities in the Busoga Region of Uganda (four facilities) and in Migori County, Kenya (16 facilities, 14 public and 2 not-for profit missionary hospitals) participated in the intervention and subsequent evaluation [35,36]. The study regions and specific health facilities were selected using stakeholder input [35,36]. In-country partners asked health facilities to participate and formal approval from facility leadership was secured prior to data

[2] Twenty-three facilities were originally assessed, but three (one county hospital in Kenya, and one district referral and one regional referral hospital in Uganda) were excluded from the PTBi matching or randomization because they did not have comparable hospitals. All 23 facilities were included in our secondary data analysis.

collection [35,36]. Among the secondary outcomes collected by the researchers was facility readiness to handle delivery and newborn complications, as measured by a facility assessment tool [35,36]. Variables assessing facilities' readiness to handle obstetric (delivery) complications were used for this thesis.

Primary data collection occurred as part of the East Africa Preterm Birth Initiative, a multi-year, multi-country initiative funded by the Bill and Melinda Gates Foundation [35,36]. The data analysis work for this MPH thesis was not funded.

Data Acquisition

Bridget, working alongside Drs. Cranmer and Sales, secured approval from UCSF, the data owner, to use the data as the data are not publicly available. Since Dr. Cranmer was involved in the cascade data collected in the parent PTBi study, UCSF did not require a formal data use agreement (DUA). Representatives from the parent study, including the original PI (Walker), the project manager, (Butrick) and representatives from both study sites (Wanyoro, Waiswa) approved of the study and committed to supporting Bridget in her secondary data analysis. The UCSF Institutional Review Board (IRB) approved the original study before data collection took place. However, as the Emory investigators (Whaley, Cranmer, Sales) were not affiliated with UCSF, they could not be added to the parent study IRB. As such, Emory IRB served as the IRB of record for the secondary data analysis.

Bridget applied for ethical approval through Emory's IRB online application, with assistance from Drs. Cranmer and Sales. Emory's IRB granted an exemption given that the dataset involved contained only facility-level data (i.e. no patient identifiers) and was deidentified by UCSF before acquisition by Emory. After the study received approval from Emory's IRB, the UCSF team directly uploaded the dataset into EmoryBox, a HIPPA-compliant mobile data storage system.

Data Analysis

Bridget led all data cleaning and analysis operations, with support from Dr. Cranmer and members of the parent study. Before the data could be analyzed, Bridget needed to rename the original variables so that variable names were more intuitive, recode text responses to numeric responses, and collapse codes on resource location. During data cleaning, Bridget found one facility that had two 2016 data entries. With the assistance of the UCSF team, Bridget was able to confirm with original data collector which result was most accurate and, therefore, appropriate for inclusion in analysis. With the assistance of Dr. Cranmer, the published literature, and input from original study team members, Bridget organized resource variables by signal function and cascade. With these initial steps completed, Bridget, supported by Dr. Cranmer and the UCSF study team members, performed the descriptive and inferential analyses described in greater detail in Chapter 4. Key indicators for the cascade estimate of emergency readiness (by emergency cascade and treatment stage) were estimated using published methods [22,25].

Write-Up

Bridget was responsible for drafting the thesis chapters and manuscript, including development of tables. Damien Scogin, a freelance graphic artist, was hired to design the report figures, in discussion with Dr. Cranmer and Bridget. Drs. Cranmer and Sales, as well as UCSF team members, provided substantive feedback throughout the writing process. Bridget, in consultation with the Emory and UCSF team members, selected *Journal of Global Health* as the journal for first manuscript submission in May of 2021.

CHAPTER 4: MANUSCRIPT

Using Clinical Cascades to Measure Facilities' Obstetric Emergency Readiness: An Analysis of Cross-Sectional Facility Assessments in Migori County, Kenya and Busoga Region, Uganda

By

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ABSTRACT

Background: Globally, hundreds of women die daily from preventable pregnancy and childbirth-related causes. Nearly 75% of these deaths are attributable to severe bleeding, infections, high blood pressure, delivery complications, and unsafe abortions. Most deaths can be avoided if deliveries are attended to by skilled professionals who have emergency management skills and strategic emergency supplies. High rates of avoidable deaths persist, especially in Sub-Saharan Africa, despite existing facility readiness estimation and intervention strategies. Facilities and health systems may benefit from more detailed analysis of emergency readiness than is currently available. This study aimed to: (1) compare estimates of facility readiness to manage common obstetric emergencies using clinical cascades and signal functions, (2) compare these estimates between countries and levels of care, and (3) test the cascading loss of emergency obstetric resources.

Methods: Data from 23 facilities in the Preterm Birth Initiative (PTBi) study were used to create signal function and clinical cascade emergency readiness estimates. Facility data were collected in 2016 from Migori County, Kenya and Busoga Region, Uganda. The cascades measure the proportion of facilities with the resources to identify the emergency, treat it, and monitor-modify therapy, as appropriate.

Results: We found four main results. First, signal functions overestimated practical emergency readiness by 22.61% across the five emergencies. Second, based on both clinical cascade and signal function estimates, not all comprehensive emergency obstetric care facilities were ready to perform basic emergency obstetric care, with estimated readiness of 58.00% and 80.00%, respectively, across the five emergencies. Third, less than half (46.96%) of facilities had all the resources necessary to identify and treat the leading causes of maternal death. Fourth, across the three stages of care and five emergencies, there was a consistent pattern of 28.41% readiness loss (SD = 3.01). Most loss occurred in the treatment stage (mean of 33.91%), though this varied by emergency.

Conclusions: Findings support growing consensus on the need to revise standard measures of obstetric emergency readiness. The cascades present step-wise, emergency-specific readiness estimates that can inform facility or health system-level policy or programs. Since accurate measurement of emergency readiness is a prerequisite for strengthening facilities' capacity to manage emergencies, the cascades may provide a more quantifiable, relevant, and actionable assessment. Future testing in varied locations and across facility levels is warranted.

BACKGROUND

In 2017, more than 800 women died daily from preventable pregnancy and childbirth related causes, totaling nearly 300,000 deaths worldwide throughout the year [1,2]. Five major complications account for nearly 75% of all maternal deaths: severe bleeding (hemorrhage), infections (sepsis), high blood pressure (pre-eclampsia and eclampsia), delivery complications (prolonged or obstructed labor), and unsafe abortions [7]. Most deaths can be prevented when deliveries are attended to by skilled professionals with the training, skills, and supplies necessary to identify and manage such emergencies—including effective triage, stabilization, and transfer when an emergency is beyond a facility's scope of management [7]. Labor complications require quick and easy access to high-quality emergency obstetric care (EmOC). Basic Emergency Obstetric Care (BEmOC) treats the majority of causes of maternal death. BEmOC requires essential supplies, durable equipment, and targeted drugs. When emergencies are beyond the capacity of BEmOC facilities, they are referred to Comprehensive Emergency Obstetric Care (CEmOC) facilities. CEmOC builds on BEmOC but also includes resources for blood transfusion and surgery [7]. Mobilizing and dispensing the clinical resources required to manage basic obstetric emergencies may be a critical step for reducing persistently elevated Maternal Mortality Ratios (MMRs) in Sub-Saharan African contexts such as Kenya and Uganda. Therefore, accurate measurement of a facility's readiness to manage common emergencies that drive the majority of deaths is urgently needed.

The World Health Organization (WHO) identified the resources necessary to manage common obstetric emergencies [5]. This approach evolved into the "signal functions," consisting of six clinical actions (three medical treatments and three manual procedures) used during obstetric emergencies. For BEmOC, the medical treatments are administering parenteral (1) antibiotics, (2) uterotonic drugs, and (3) anticonvulsants/antihypertensives [3]. The manual procedures include (4) manually removing retained placentas, (5) removing retained products of

conception, and (6) performing assisted vaginal deliveries [3]. CEmOC adds two additional actions: perform (7) surgery (e.g. caesarean section) and (8) blood transfusion [3]. Specific items (tracers) are used as proxies to measure a facilities' ability to handle obstetric emergencies in the signal function model [3,8-13]. Thus, all CEmOC facilities should be prepared to perform all BEmOC signal functions (and have all the resources necessary to do so), in addition to performing surgery and blood transfusion.

The signal functions are the dominant method for assessing obstetric emergency readiness at facilities worldwide [15,16,45,66]. It provides one aggregate estimate of overall facility readiness—the percent of tracer items present at the facility [45]. However, in recent years, scientists and practitioners have increasingly called for revised approaches [9,11,17-22]. One particular weakness is the model's inability to predict readiness for *specific* emergencies [17,19]. Further, this approach does not identify strategic resources for managing multiple emergencies or suggest indicators for system-wide emergency readiness [22]. Also, the signal functions do not specify the resources required to first *identify* the emergency/disorder or the consumable supplies and durable goods required to deliver the treatment or perform the procedure [22]. Thus, to further reduce delivery-related mortality, we need a more robust set of measurable indicators that are emergency/outcome-specific and relevant for multiple levels of the health system [22].

The cascade model is a clinically-oriented approach to measuring facility readiness by reporting the step-wise cascading relationship between emergency resources [22-24]. The cascade model defines emergency readiness as the proportion of facilities that can *identify* an emergency and have the resources (including drugs, supplies, and equipment) to *treat* the identified emergency. The ability to *monitor and modify* the initial treatment as clinically indicated has been proposed as a care quality metric [22].

Unlike the wealth of research on signal functions, the clinical cascades have been tested in fewer geographic locations. Moreover, as an emerging metric, there are limited studies

comparing the clinical cascades and signal functions as methods to assess facilities' readiness to handle basic obstetric emergencies. To date, only one study compared signal function and clinical cascade estimates of readiness. Conducted among a sample of facilities in Kakamega County, Kenya, the study found that, across the five maternal emergencies driving maternal mortality, the signal functions overestimated practical emergency management readiness by 55% [22]. Moreover, a consistent readiness loss of 33% across all cascades (emergencies) and stages of care (identification, treatment, monitor/modify) emerged [22]. Similarly, a study examining the clinical cascades as applied to neonatal care in Kenya and Uganda confirmed a mean readiness loss of 30% across all cascades and stages [25]. This study, however, did not compare clinical cascade estimates of readiness against signal function estimates since there are not standard signal function indicators for newborn emergencies. The findings from these two studies warrant additional investigation into the relevance and transferability of cascade analysis to additional global contexts, health systems, and levels of facility care. A more comprehensive analysis of a facility's readiness to handle obstetric emergencies, such as the cascade analysis, may be critical to guide emergency-specific or supply-specific interventions to close gaps in emergency supplies.

METHODS

Aims

Building off the wealth of research on the signal functions and the formative research on clinical cascades, this study was designed to assess emergency readiness at BEmOC and CEmOC facilities in Kenya and Uganda. This analysis of emergency obstetric readiness is nested in a pair-matched, cluster randomized controlled trial evaluating a package of facility-based interventions to improve care for preterm infants [35]. More specifically, this study aimed to: (1) compare estimates of facility readiness to manage common obstetric emergencies using clinical cascades and signal functions, (2) compare these estimates between countries and levels of care, and (3) test the cascading loss of emergency obstetric resources. The limited available published research

suggested that the signal functions would estimate a higher level of preparedness than that estimated by the clinical cascades and that overall estimates of readiness would be higher among higher-level facilities [22,25].

Study Design and Data Collection

We conducted an analysis of data collected by the Preterm Birth Initiative Kenya and Uganda Implementation Research Collaborative (PTBi) in 2016-2019 as part of a pair-matched, cluster randomized controlled trial evaluating a package of facility-based interventions to improve care for preterm infants [35]. Data from facility assessments at all 23 facilities in the PTBi study were used to create both the signal function and clinical cascade estimates of emergency obstetric readiness [35]. Data from all 17 PTBi facilities in Migori County (western Kenya) and 6 in Busoga Region (eastern Uganda) were used in this study. During data collection, research assistants used standardized forms to visually identify emergency resources in the facilities. The inventory captured data on facility demographics, obstetric drugs, consumable supplies, durable goods, and guidelines and protocols. For this nested study, we used the baseline data prior to PTBi intervention (2016) to accurately capture standard facility readiness prior to intervention.

Emergency Readiness

Signal Functions

The WHO's Service Readiness Index (SRI) defines a facility's obstetric emergency readiness using the six clinical actions that define BEmOC [3]. In the SRI methodology, a facility's overall obstetric emergency readiness is defined using the average number of tracer items present on the day of the facility assessment [16,45]. Traditionally, signal function readiness estimates are reported as a single indicator, the proportion of facilities with the tracer items for all medical treatments and manual procedures [22]. However, for the purposes of our analysis, we reported: (1) total readiness estimate across all signal functions, (2) readiness

estimates by type of signal function (medical treatment vs. manual procedure), and (3) individual readiness estimates for each signal function. This allowed for a direct comparison to the clinical cascade estimates.

Clinical Cascades

For the purpose of comparison to the signal functions, mean clinical cascade readiness was defined using stages 1 and 2 of the clinical cascades as the signal functions do not have quality indicators for monitoring and modifying the primary emergency treatment based on the patient's clinical response. We measured clinical cascade estimates of readiness across facilities at the individual resource level (**Table 1** and **Table 2**). This allowed us to demonstrate precisely where in the clinical cascade of care facilities' readiness drops off. We then aggregated these results to determine overall readiness as defined by the clinical cascades, as well as to explore at which stage(s) within the cascade most readiness was lost.

Operational Definitions

In the absence of certain variables, we used alternative variables as proxies for the missing tracer items in order to not unduly penalize a facility's readiness estimate. This was especially true for consumable supplies and durable goods. In other instances, neither the tracer item of interest nor a proxy item were obtained during the facility inventory. This was true for most tracers from the assisted vaginal delivery cascade. Consequently, we were unable to measure assisted vaginal delivery readiness using the signal functions or cascades. Some tracer items are not concretely defined in the signal functions model. When drugs were not explicitly defined by the signal functions, we referred to the WHO first-line recommendations for obstetric care [3,67,68]. For instance, in the signal functions, antibiotics are broadly defined as "parenteral antibiotics." To transform this into a specific, measurable variable, we deferred to the WHO's 3-step sequence of obstetric antibiotic therapy escalation to define readiness (ampicillin, gentamicin, and metronidazole) [3,67,68].

Analysis

During data collection, researchers recorded both the presence/absence of the item and its location (e.g. Maternity, Labor and Delivery, Antenatal, Newborn Units). However, for this analysis, only resource presence/absence was used to estimate facility-level readiness regardless of location [3,22,47].

We described obstetric variable availability with standard descriptive statistics. We reported percentages and frequencies for categorical variables and medians with interquartile ranges (IQR) for continuous variables since variables were not normally distributed (e.g., delivery volume). Aggregate readiness across multiple emergencies or multiple stages was reported as the overall mean. Drop-offs in readiness between each stage and across each cascade were reported as percentages, with accompanying measures of spread (i.e. standard deviation, SD). We reported estimates of overall emergency readiness as means for several reasons: 1) the SRI methodology, upon which this study is based, reports means, (2) reporting means is in line with the previously published literature, and (3) with so few observations, the median would not effectively capture central tendency.

For the purposes of comparison across the two measures, we reported: (1) total readiness estimates across all signal functions/clinical cascades, (2) readiness estimates by type of signal function (medical treatment vs. manual procedure), (3) individual readiness estimates for each signal function/clinical cascade, and (4) overestimate readiness. Mean overall readiness was calculated by averaging across all five signal functions or clinical cascades. Overestimated readiness was calculated by subtracting the clinical cascade estimate of readiness from the signal function estimate. These results were reported for all facilities and stratified by country (Kenya vs. Uganda) and reported c-section capability. Reported c-section services were used as a proxy for CEmOC facilities since BEmOC facilities do not have this capability.

For the purpose of calculating readiness loss according to the clinical cascade model, we reported readiness loss by stage of the clinical cascade, by emergency, and as overall readiness

loss across the three stages and five emergencies. To determine readiness loss by stage, we subtracted readiness at the end of a stage from readiness at the end of the preceding stage. To calculate readiness loss during stage 1, we subtracted readiness at the end of the stage from 100.00%. We then calculated the mean and SD across the five clinical cascades for each stage to generate the mean loss across each stage (Identify, Treat, Monitor-Modify). From these readiness loss estimates, we calculated readiness loss by clinical cascade by averaging the readiness loss across the three stages for each clinical cascade, thus producing five estimates of mean loss. After determining the mean loss for each clinical cascade, we found the mean of these five estimates to determine the overall readiness loss across emergencies and stages. We applied these same calculations among only (1) government facilities, (2) mission facilities, and (3) the three referral facilities. We also stratified (4) government facility estimates by country and (5) all facilities (inclusive of both government and mission) by reported c-section capability. For these five sub-analyses, we tested readiness estimates for significance using Fisher's Exact Test. We used Fisher's Exact instead of Chi-Square due to the small sample sizes. We tested for significance at both stage 2 and stage 3 of the clinical cascade of care.

Ethics

The trial gained ethical approval from the Kenya Medical Research Institute, Makerere University School of Public Health, and the UCSF Institutional Review Boards (IRBs) prior to primary data collection. Emory University's IRB determined the nested analysis of personally de-identified data was exempt from oversight (August 20, 2020).

RESULTS

Facility Characteristics

Of the 23 facilities, 82.61% were government owned across both countries (**Table S1** in the **Online Supplementary Document)**. The remaining 17.39% were mission hospitals. Among government facilities in Uganda, three-fourths were District Hospitals. These facilities offer

outpatient, inpatient, laboratory, emergency surgical, and maternity services [69]. They are designed to have blood transfusion and x-ray services [69]. Among facilities in Kenya, 4 (2 mission and 2 government (subcounty and teaching and referral hospitals)) offer CEmOC while the other 13 (subcounty and health centers) only offer BEmOC. Across both countries, slightly less than half of facilities (43.48%) had c-section capability. The median annual delivery volume in Kenya facilities (598.91, IQR = 504.00) was much lower than Uganda's (2,662.5, IQR = 3,336.70, **Table S2** in the **Online Supplementary Document)**.

Emergency Obstetric Resource Availability

There was wide variability across facilities in the availability of the consumable supplies and durable goods that define the clinical cascades. On average, consumable supplies were present in 77.64% of facilities. The most widely available resources were those involved in the intravenous administration of drugs and fluids. Specifically, IV fluid (defined as Normal Saline or Ringer's Lactate), was present in 95.65% of facilities, while IV cannula/catheter and IV tubing were both present in 86.96% of facilities. By contrast, urine collection cups and urine dipsticks were the least available consumable supplies, present in 56.52% of facilities. For durable goods, while a few (i.e. speculum and power) were present in all facilities, others (e.g. oxygen heads and cylinders) were present in around one-third of facilities (30.43% and 39.13%, respectively). We found even greater variability in the availability of drugs. The most widely available class of drugs was anesthetic, with Lidocaine present in 91.30% of facilities. The least readily available class of drugs was uterotonics. Though Oxytocin was present in 91.30% of facilities, Misoprostol was available in around one-third (34.78%) of facilities and Ergometrine in less than 5% (4.35%). Overall, guidelines and protocols were not widely available, available on average in 33.54% of facilities. See **Tables S3-S6** in the **Online Supplementary Document** for the full results.

Signal Function Estimates of Emergency Readiness

Across the three medical treatments and two manual procedures, the signal functions produced a mean overall readiness of 69.57% (**Table 3)**. Readiness estimates were fairly consistent across the five maternal signal functions, ranging from 60.87% (oxytocic) to 78.26% (anticonvulsant), and were identical across medical and manual signal functions (69.57%).

As expected, signal function estimates differed by level of care (i.e. c-section capability). Mean overall readiness across the five signal functions was 80.00% among facilities with c-section capability (**Table 4),** compared to 61.54% among facilities without c-section capability (**Table 5**).

When stratified by country, we found higher signal function estimates of readiness among Ugandan (mean readiness of 73.33%, **Table S7** in the **Online Supplementary Document**) than among Kenyan facilities (mean readiness of 68.24%, **Table S8** in the **Online Supplementary Document**).

Clinical Cascades

Overall Readiness

Across all five emergencies, the signal function model overestimated obstetric emergency readiness by 22.61% (**Figure 1**; **Table 3**). The mean signal function estimate of readiness was 69.57%; however, readiness measured by stage 2 of the cascade model, was substantially lower at 46.96%. Notably, there was wide variability of overestimation by signal function, ranging from 0.00% (oxytocic) to 52.17% (anticonvulsant). By signal function, the mean overestimates were: Antibiotic (21.74%); Oxytocic (0.00%); Anticonvulsant (52.17%); Retained Placenta (26.09%); and Retained Products of Conception (13.05%).

The 23% overestimation remained largely consistent after stratifying by c-section capability and country, with 0.26%- 0.72% difference in overestimation between the total sample and stratified estimates. Among facilities with c-section capability, there was a 22.00%

overestimation **(Table 4)**, and among those without c-section capability, there was a 23.08% overestimation **(Table 5).** Similarly, among Kenyan facilities, there was a 22.35% overestimation (**Table S7** in the **Online Supplementary Document)**, and among Ugandan facilities, there was a 23.33% overestimation (**Table S8** in the **Online Supplementary Document)**.

Readiness Loss by Cascade

There were differences in readiness loss along the cascades from identification of the disorder through monitoring and modifying treatment (**Figure 2**; **Table 6).** It varied least for the sepsis cascade (SD = 5.02) and most for the hypertension cascade (SD = 35.41). There was also substantial variability in *when* readiness was lost along the cascade of clinical obstetric care. For hypertensive emergency, the majority of readiness was lost when identifying the emergency (69.57%). In contrast, 0.00% readiness was lost in this stage for the hemorrhage, retained placenta, and incomplete abortion cascades. Of note, stage 1 of the hemorrhage and retained placenta cascades rely on staff skill alone, which was assumed to be 100%. Thus, there is not a physical commodity required to estimate identification readiness for these emergencies. Consequently, the full emergency identification based on staff skill likely overestimates actual readiness [22]. See **Figure 3** for the hemorrhage clinical cascade, **Figure 4** for the retained placenta clinical cascade, and **Figures S1-S3** in the **Online Supplementary Document** for the remaining clinical cascades.

When examining government-owned and mission facilities, separately, the pattern and overall readiness loss along the cascade were more consistent to the results of the full sample among government-owned (**Table S9** in the **Online Supplementary Document**) than among mission facilities (**Table S10** in the **Online Supplementary Document**). Likewise, when examining only the three facilities that serve as referral facilities, though we found nuanced differences in patterns of readiness loss across a few emergencies, results were overall similar to those found in the full sample (**Table S11** in the **Online Supplementary Document**).

When examining readiness loss by country and level of care (i.e. c-section capability), there were subtle differences. Across stages of care at Kenyan government facilities, loss varied least for sepsis (SD = 7.70) and most for hypertensive emergencies (SD = 40.55, **Table S12** in the **Online Supplementary Document**). Across stages in Uganda, loss varied least for hypertensive emergencies (SD = 14.43) and sepsis (SD = 14.43) but most for hemorrhage (SD = 38.19) and retained placenta (SD = 38.19, **Table S13** in the **Online Supplementary Document**). Moreover, patterns of readiness loss across stages were not consistent for all emergencies. In both the hemorrhage and retained placenta cascades, the most readiness was lost in stage 2 for Kenyan facilities (46.67% and 73.33%) and stage 3 for Ugandan facilities (75.00% for both cascades). Likewise, for the sepsis cascade, the most readiness was lost in stage 2 for Kenyan facilities (33.33%) and stage 1 for Ugandan facilities (50.00%).

Across stages of care at facilities with c-section capability, loss varied least for sepsis (SD = 17.32) and most for hemorrhage (SD = 30.00, **Table S14** in the **Online Supplementary Document**). Alternatively, among facilities without c-section capability, we saw the same pattern as appeared among the full sample – loss varied least for sepsis (SD = 11.75) and most for hypertensive emergencies (SD = 42.37, **Table S15** in the **Online Supplementary Document).** As was true in the full sample, among both facilities with and without reported c-section capability, for hypertensive emergencies, the majority of readiness was lost when identifying the emergency (60.00% and 76.92%, respectively), while 0.00% readiness was lost in this stage for the hemorrhage, retained placenta, and incomplete abortion cascades.

Readiness Loss by Stage

There was a consistent pattern of 28.41% overall readiness loss across emergencies and stages (SD = 3.01) despite moderate variability in how loss occurred across these stages (average SD across stages = 24.17, **Figure 5; Table 6**). The largest amount of loss occurred in treating the

disorder. The loss across all five cascades was 19.13% for emergency-identification (stage 1), 33.91% for treatment (stage 2), and 32.17% for monitor and modify treatment (stage 3).

Readiness loss by stage results were profoundly similar when examining only government facilities (**Table S9** in the **Online Supplementary Document**). There was a consistent pattern of 29.12% overall readiness loss across emergencies and stages (SD = 2.35) despite again seeing wide variability in how loss occurred across these stages (average SD across stages = 24.71). Among only mission facilities, there was a less consistent pattern of 25.00% overall loss across emergencies and stages (SD = 10.21) and greater variability in how loss occurred across these stages (average SD across stages = 35.73, **Table S10** in the **Online Supplementary Document**). When examining only the three referral facilities, we found a perfectly consistent pattern of 22.22% overall readiness loss across emergencies and stages (SD = 0.00) and wide variability in how loss occurred across these stages (average SD across stages = 30.79, **Table S11** in the **Online Supplementary Document**).

Among Kenyan government facilities, there was a consistent pattern of 28.00% overall loss across emergencies and stages (SD = 2.98) and wide variability in how loss occurred across these stages (average SD across stages = 27.43, **Table S12** in the **Online Supplementary Document**). Among government facilities in Uganda, we saw a perfectly consistent readiness loss of 33.33% across all emergencies and stages (SD = 0.00) and wide variability in how loss occurred across these stages (average SD across stages = 26.82, **Table S13** in the **Online Supplementary Document**). Consistent with the unstratified results, the largest amount of loss among Kenyan facilities occurred in treating the disorder (40.00%). However, among Ugandan facilities, the largest amount of loss occurred in the final stage of the cascade—monitoring and modifying therapy (50.00%).

Among facilities with reported c-section capability, there was a consistent pattern of 26.67% overall loss across emergencies and stages (SD = 4.08) and large variability in how loss occurred across these stages (average SD across stages = 24.82, **Table S14** in the **Online**

Supplementary Document). Among facilities with no reported c-section capability, we saw a consistent readiness loss of 29.74% across all emergencies and stages (SD = 3.44), while seeing even wider variability in how loss occurred across these stages (average SD across stages = 29.49, **Table S15** in the **Online Supplementary Document**). Consistent with the unstratified results, the largest amount of loss among facilities without c-section capability occurred in treating the disorder (43.08%). However, among facilities with c-section capability, the largest amount of loss occurred in the final stage of the cascade—monitoring and modifying therapy (38.00%).

Clinical Cascade Estimates of Readiness by Co-Factors

Except for higher proportions of stage 2 readiness for the retained placenta cascade among facilities with reported c-section capability compared to those without (70.00% versus 23.08%, p = 0.04) and mission facilities compared to government facilities (100.00% versus 36.84%, p = 0.02), we found no statistically significant differences in clinical cascade readiness estimates among the sub-analyses (**Table S16** in the **Online Supplementary Document).**

DISCUSSION

This study expands the global scholarship on measuring obstetric emergency readiness at health facilities. In line with the one previously published comparison of the two methods, we saw an overestimation of obstetric emergency readiness by the signal functions. However, our mean overestimation across emergencies (22.61%) was less than half of that reported in the previous study (54.48%) [22]. The difference in magnitude could be attributable to differences in facility characteristics, as 43% of these facilities were CEmOC while all were BEmOC in the Western Kenya study. [22]. Moreover, there was slight variation in the resources used to construct the signal functions and clinical cascades between the two studies, with changes made based on updated WHO guidelines at the time of this study and some operational definitions

differing between studies. Despite some operational and contextual differences, any overestimation of practical readiness is clinically salient. The 22.61% overestimation of readiness in this study—particularly including CEmOC facilities—is profoundly concerning for advancing global maternal survival.

As was also the case in the two previous studies that examine clinical cascades as a measure of emergency readiness, we found readiness was consistently lost across the stages of care. The largest drop off occurs in treating the disorder (33.91%). We found a consistent pattern of 28.41% overall readiness loss across emergencies and stages (SD = 3.01). The study of 44 BEmOC facilities in Kenya found a consistent 33.03% mean loss across the five emergencies and three stages of care [22]. Moreover, in a study of the clinical cascades as applied to neonatal emergencies, the mean readiness loss was 30.00% across emergencies and stages [25]. Since the 30% aggregate loss for neonatal emergencies comes from the same facilities used in this maternal cascade study, this mean loss indicator may be a system-level indicator of emergency readiness loss as previously proposed. Together, these three studies suggest a consistent readiness loss of approximately 30% across emergencies and stages in both maternal and neonatal contexts across countries.

This study expanded upon the previously published comparison by examining overestimation between countries and levels of care. Overall estimates of readiness (according to both signal functions and clinical cascades) were higher among Ugandan facilities than Kenyan facilities. This result was expected given the level of health facilities included in each country sample. Ugandan facilities were primarily larger, regional hospitals, while in Kenya, they were primarily smaller, subcounty and health center facilities. We also found differences in readiness estimations by level of care (among CEmOC versus BEmOC facilities). By definition, all facilities with c-section capability are CEmOC facilities that should be prepared to manage all BEmOC signal functions in addition to performing c-sections and blood transfusion. However, this study demonstrated that even CEmOC facilities were not ready to perform all BEmOC

functions. This gap was present when CEmOC facility emergency readiness was estimated with both the signal functions (80.00%) and clinical cascades (58.00%). This suggested that CEmOC facilities were not equipped to handle the level of care that their facility designation requires. If seen across a larger sample, the results could suggest the need for additional investment to equip CEmOC facilities to handle the full range of obstetric emergencies.

However, this study is not without limitations. It includes data from a single timepoint in two regions of East Africa. Given the unpredictable availability of consumable resources and drugs, as evidenced by both the published literature and an informal review of data collection notes, a single timepoint may be insufficient to capture a complete picture of a facility or system's readiness [19,48]. Collecting data from the same set of facilities at more frequent intervals could not only provide more accurate readiness data, but also point to patterns in availability based on supply procurement. Moreover, in the absence of necessary variables, we had to use alternative variables as proxies for the missing tracer items. These proxies may not capture the nuances of actual resource availability. For instance, facilities without electricity may use kerosine-powered refrigerators. With information on neither refrigeration nor kerosine, we used electricity as a proxy for refrigeration. Facilities without electricity, but with kerosine-powered refrigerators would, therefore, be reported as lacking refrigeration in our analyses. More broadly, measuring the availability of resources, alone, does not account for the quality of such resources nor clinicians' ability to use the resources effectively in clinical care [25,49]. Information on resource functionality (e.g. drug expiration dates), facility staffing levels, and clinician knowledge and skillset would allow for a more precise estimate of practical emergency readiness at the facility level. This analysis did not account for the location of resources and we could not determine how easily accessible resources were during emergencies on various units. Given the importance of time in an emergency, resource location and availability is critical and should be explored in future research. Lastly, future research should link cascade estimates of

readiness to facilities' adverse clinical outcomes (e.g., maternal mortality ratio, maternal near miss, severe maternal outcomes, or prevalence of specific emergencies).

Despite these limitations, our study offers important contributions to the emerging evidence on the clinical cascades as a more precise and targeted alternative to signal function estimates of emergency readiness. This adds to the mounting concerns regarding the accuracy of the signal functions as an indicator of practical obstetric emergency readiness in the real world. By defining the resources necessary to identify and treat emergencies and monitor and modify treatment as clinically indicated, the cascades provide a detailed, stepwise analysis of resource availability and a novel set of readiness indicators. Cascade findings allow us to see precisely where readiness is lost. Loss can be estimated at the stage of care, emergency, or individual resource level. There is growing—albeit preliminary—evidence that the variance of loss across stages and cascades may provide an indicator of emergency readiness at the system level. Results from this study may inform strategies that optimize emergency commodity provision for Kenyan and Ugandan facilities and strengthen system-level strategies for emergency-specific maternal survival. Measuring readiness according to the clinical cascades requires a marginal increase in effort during data collection but provides a more nuanced picture of clinical care. Further investigation in diverse contexts is warranted and could suggest a need to shift away from the standard readiness metrics (such as the signal functions and SRI) toward more nuanced, precise and practical estimates offered by the cascades.

CONCLUSIONS

In conclusion, emergency obstetric care is critical in managing the obstetric complications driving elevated maternal mortality ratios in Sub-Saharan Africa, therefore requiring an accurate measurement of readiness to handle such complications. In line with previously published research, our study suggests the need to reconsider the signal functions as

the preferred method of measuring readiness. Measuring readiness according to the clinical cascades requires a marginal increase in effort during data collection but provides a more nuanced picture of clinical care that can be used to guide strategies that optimize emergency commodity provision and strengthen system-level strategies for emergency-specific maternal survival.

Table 1. Cascade Emergency Readiness Stratified by Medical Signal Function

Clinical Cascade (*Signal Function*)	**Cascade Stage**	**Item**	**%**	**n** [1]
Manage Sepsis-Infection (*Antibiotic*)	Identify	Thermometer	95.65	22
		Stethoscope	78.26	18
		Sphygmomanometer	73.91	17
	Treat (Consumables)	IV Tubing	60.87	14
		IV Cannula/Catheter	52.17	12
		IV Fluid [2]	52.17	12
	Treat (Durables)	IV Pole	52.17	12
	Treat (Treatment)	Parenteral Antibiotic - Step 1 [3]	52.17	12
		Parenteral Antibiotic - Step 2 [4]	47.83	11
	Monitor + Modify	Protocol: Sepsis [5]	30.43	7
Manage Hemorrhage (*Oxytocic*)	Identify	Staff skill [6]	100.00	23
	Treat (Consumables)	Gloves [7]	78.26	18
		IV Tubing	69.57	16
		IV Cannula/Catheter	65.22	15
		IV Fluid [2]	65.22	15
	Treat (Durables)	IV Pole	65.22	15
		Refrigeration [8]	65.22	15
	Treat (Treatment)	Parenteral Uterotonic [9]	60.87	14
	Monitor + Modify	Sphygmomanometer	52.17	12
		Stethoscope	52.17	12
		Uterotonic, non-oxytocin [10]	21.74	5
		Urinary Catheter	21.74	5
		Oxygen Source [11]	21.74	5

		Oxygen Tubing	17.39	4
		Oxygen Delivery [12]	17.39	4
		Protocol: Hemorrhage	13.04	3
Manage Hypertensive Emergencies (*Anticonvulsant*)	Identify	Sphygmomanometer	91.30	21
		Stethoscope	78.26	18
		Urine Cup	43.48	10
		Urine Dipstick	30.43	7
	Treat (Consumables)	IV Tubing	30.43	7
		IV Cannula/Catheter	26.09	6
		IV Fluid [2]	26.09	6
	Treat (Durables)	IV Pole	26.09	6
	Treat (Treatment)	Parenteral Anticonvulsant [13]	26.09	6
		Parenteral Antihypertensive [14]	26.09	6
	Monitor + Modify	Urinary Catheter	26.09	6
		Calcium Gluconate	17.39	4
		Oxygen Source [11]	17.39	4
		Oxygen Tubing	13.04	3
		Oxygen Delivery [12]	13.04	3
		Protocol: Eclampsia	13.04	3

[1] Total sample n = 23 facilities
[2] Either normal saline (NS) or lactated ringer's (LR).
[3] Parenteral ampicillin or parenteral penicillin
[4] Parenteral gentamicin or cefotaxime/ceftriaxone
[5] Puerperal Sepsis, Infection, or Antibiotic Administration Protocol
[6] 100% staff skill for identifying the emergency was assumed
[7] Sterile gloves or clean disposable latex gloves (represented as a single variable in the original dataset)
[8] Power used as proxy for refrigeration
[9] Oxytocin (neither Tranexamic Acid nor Carbetocene available in the dataset)
[10] Misoprostol tablets or ergometrine (IM)

(11) Oxygen concentrator and power or oxygen cylinder and oxygen head
(12) Oxygen mask or nasal cannula
(13) Magnesium sulfate (IV)
(14) Hydralazine or Labetalol or Nifedipine or Methyldopa

Table 2. Cascade Emergency Readiness Stratified by Manual Signal Function

Clinical Cascade (*Signal Function*)	**Cascade Stage**	**Item**	**%**	**N** [1]
Manage Retained Placenta (*Manual removal of retained placenta*)	Identify	Staff Skill [2]	100.00	23
		Light Source [3]	100.00	23
	Treat (Consumables)	Gloves [4]	78.26	18
		IV Tubing	69.57	16
		IV Cannula/Catheter	65.22	15
		IV Fluid [5]	65.22	15
	Treat (Durables)	IV Pole	65.22	15
		Refrigeration [6]	65.22	15
	Treat (Treatment)	Parenteral Uterotonic [7]	60.87	14
		Parenteral Sedative - hypnotic [8]	43.48	10
		Parenteral Antibiotic – Step 1 [9]	43.48	10
	Monitor + Modify	Sphygmomanometer	34.78	8
		Stethoscope	34.78	8
		Uterotonic, non-oxytocin [10]	17.39	4
		Parenteral Antibiotic - Step 2 [11]	13.04	3
		Urinary Catheter	13.04	3
		Protocol(s) [12]	8.70	2
Manage Incomplete Abortion (*Manual removal of retained products of conception*)	Identify	Speculum	100.00	23
		Light Source [3]	100.00	23
	Treat (Consumables)	Gloves [4]	78.26	18
		IV Tubing	69.57	16
		IV Cannula/Catheter	65.22	15
		IV Fluid [5]	65.22	15

	Treat (Durables)	Manual Vacuum Aspirator Kit [13]	56.52	13
		IV Pole	56.52	13
	Treat (Treatment)	Local Anesthetic [14]	56.52	13
		Parenteral Antibiotic - Step 1 [9]	56.52	13
	Monitor + Modify	Sphygmomanometer	52.17	12
		Stethoscope	47.83	11
		Refrigeration [6]	47.83	11
		Uterotonic, non-oxytocin [10]	17.39	4
		Parenteral Antibiotic - Step 2 [11]	13.04	3
		Urinary Catheter	13.04	3
		Protocol(s) [15]	8.70	2

[1] Total sample n = 23 facilities
[2]100% staff skill for identifying the emergency was assumed
[3] Flashlight or power (as proxy for electric lights)
[4] Sterile gloves or clean disposable latex gloves (represented as single variable in the dataset)
[5] Either normal saline (NS) or lactated ringer's (LR)
[6] Power used as proxy for refrigeration
[7] Oxytocin
[8] Diazepam (IV)
[9] Parenteral ampicillin or parenteral penicillin
[10] Misoprostol tablets or ergometrine (IM)
[11] Parenteral gentamicin or cefotaxime/ceftriaxone
[12] Retained placenta protocol or hemorrhage protocol or infection protocol
[13] Manual vacuum device and cannula
[14] Lidocaine
[15] Incomplete abortion protocol or hemorrhage protocol or infection protocol

Table 3. Comparison of Emergency Readiness Using Clinical Cascades and Signal Functions, Full Sample [1]

Clinical Cascade	**Signal Functions**	**Clinical Cascades**	**Overestimated Readiness**
(Signal Function)	**% Readiness, Tracer Items**	**% Readiness, Stage 2**	**[Signal Functions (-) Cascade]**
Medical Treatments			
Manage Sepsis - Infection *(Antibiotic)* [2]	69.57%	47.83%	21.74%
Manage Hemorrhage *(Oxytocic)* [3]	60.87%	60.87%	0.00%
Manage Hypertensive Emergency *(Anticonvulsant)* [4]	78.26%	26.09%	52.17%
Mean Medical Readiness	69.57%	44.93%	24.64%
Manual Procedures			
Manage Retained Placenta *(Manual removal of retained placenta)* [5]	69.57%	43.48%	26.09%
Manage Incomplete Abortion *(Manual removal of retained products of conception)* [6]	69.57%	56.52%	13.05%
Mean Manual Readiness	69.57%	50.00%	19.57%
	69.57%	**46.96%**	**22.61%**
Mean Overall Readiness:	*Signal Function Estimate*	*Cascade Estimate*	*% Overestimated by Signal Functions*

[1] n = 23 facilities
[2] IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin, and gentamicin or cefotaxime or ceftriaxone
[3] Gloves, IV fluids, IV cannula/catheter, IV tubing, oxytocin or misoprostol or ergometrine
[4] IV fluids, IV cannula/catheter, IV tubing, magnesium sulfate
[5] Flashlight or power, IV fluids, IV cannula/catheter, IV tubing, oxytocin, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone
[6] Flashlight or power, MVA kit, IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone

Table 4. Comparison of Emergency Readiness Using Clinical Cascades and Signal Functions, Facilities with Reported C-Section Capability [1]

Clinical Cascade	**Signal Functions**	**Clinical Cascades**	**Overestimated Readiness**
(Signal Function)	**% Readiness, Tracer Items**	**% Readiness, Stage 2**	**[Signal Functions (-) Cascade]**
Medical Treatments			
Manage Sepsis - Infection *(Antibiotic)* [2]	90.00%	50.00%	40.00%
Manage Hemorrhage *(Oxytocic)* [3]	70.00%	70.00%	0.00%
Manage Hypertensive Emergency *(Anticonvulsant)* [4]	90.00%	30.00%	60.00%
Mean Medical Readiness	83.33%	50.00%	33.33%
Manual Procedures			
Manage Retained Placenta *(Manual removal of retained placenta)* [5]	70.00%	70.00%	0.00%
Manage Incomplete Abortion *(Manual removal of retained products of conception)* [6]	80.00%	70.00%	10.00%
Mean Manual Readiness	75.00%	70.00%	5.00%
	80.00%	**58.00%**	**22.00%**
Mean Overall Readiness:	*Signal Function Estimate*	*Cascade Estimate*	*% Overestimated by Signal Functions*

[1] n = 10 facilities
[2] IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin, and gentamicin or cefotaxime or ceftriaxone
[3] Gloves, IV fluids, IV cannula/catheter, IV tubing, oxytocin or misoprostol or ergometrine
[4] IV fluids, IV cannula/catheter, IV tubing, magnesium sulfate
[5] Flashlight or power, IV fluids, IV cannula/catheter, IV tubing, oxytocin, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone
[6] Flashlight or power, MVA kit, IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone

Table 5. Comparison of Emergency Readiness Using Clinical Cascades and Signal Functions, Facilities with No Reported C-Section Capability [1]

Clinical Cascade	**Signal Functions**	**Clinical Cascades**	**Overestimated Readiness**
(Signal Function)	**% Readiness, Tracer Items**	**% Readiness, Stage 2**	**[Signal Functions (-) Cascade]**
Medical Treatments			
Manage Sepsis - Infection *(Antibiotic)* (2)	53.85%	46.15%	7.70%
Manage Hemorrhage *(Oxytocic)* [3]	53.85%	53.85%	0.00%
Manage Hypertensive Emergency *(Anticonvulsant)* [4]	69.23%	23.08%	46.15%
Mean Medical Readiness	58.98%	41.03%	17.95%
Manual Procedures			
Manage Retained Placenta *(Manual removal of retained placenta)* [5]	69.23%	23.08%	46.15%
Manage Incomplete Abortion *(Manual removal of retained products of conception)* [6]	61.54%	46.15%	15.39%
Mean Manual Readiness	65.39%	34.62%	30.77%
	61.54%	**38.46%**	**23.08%**
Mean Overall Readiness:	*Signal Function Estimate*	*Cascade Estimate*	*% Overestimated by Signal Functions*

[1] n = 13 facilities
[2] IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin, and gentamicin or cefotaxime or ceftriaxone
[3] Gloves, IV fluids, IV cannula/catheter, IV tubing, oxytocin or misoprostol or ergometrine
[4] IV fluids, IV cannula/catheter, IV tubing, magnesium sulfate
[5] Flashlight or power, IV fluids, IV cannula/catheter, IV tubing, oxytocin, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone
[6] Flashlight or power, MVA kit, IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone

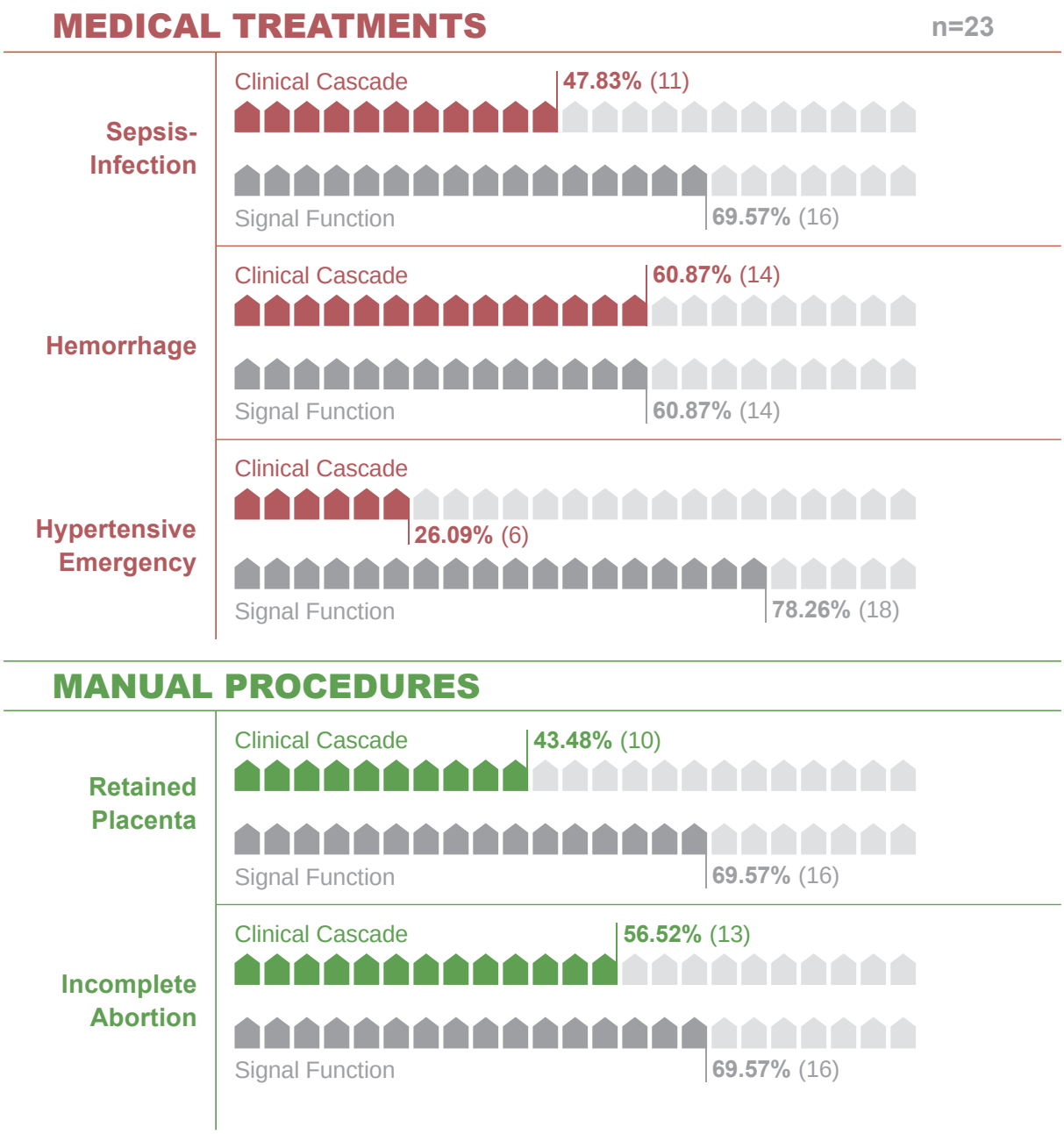

Figure 1. Signal Function versus Clinical Cascade Estimates of Emergency Readiness

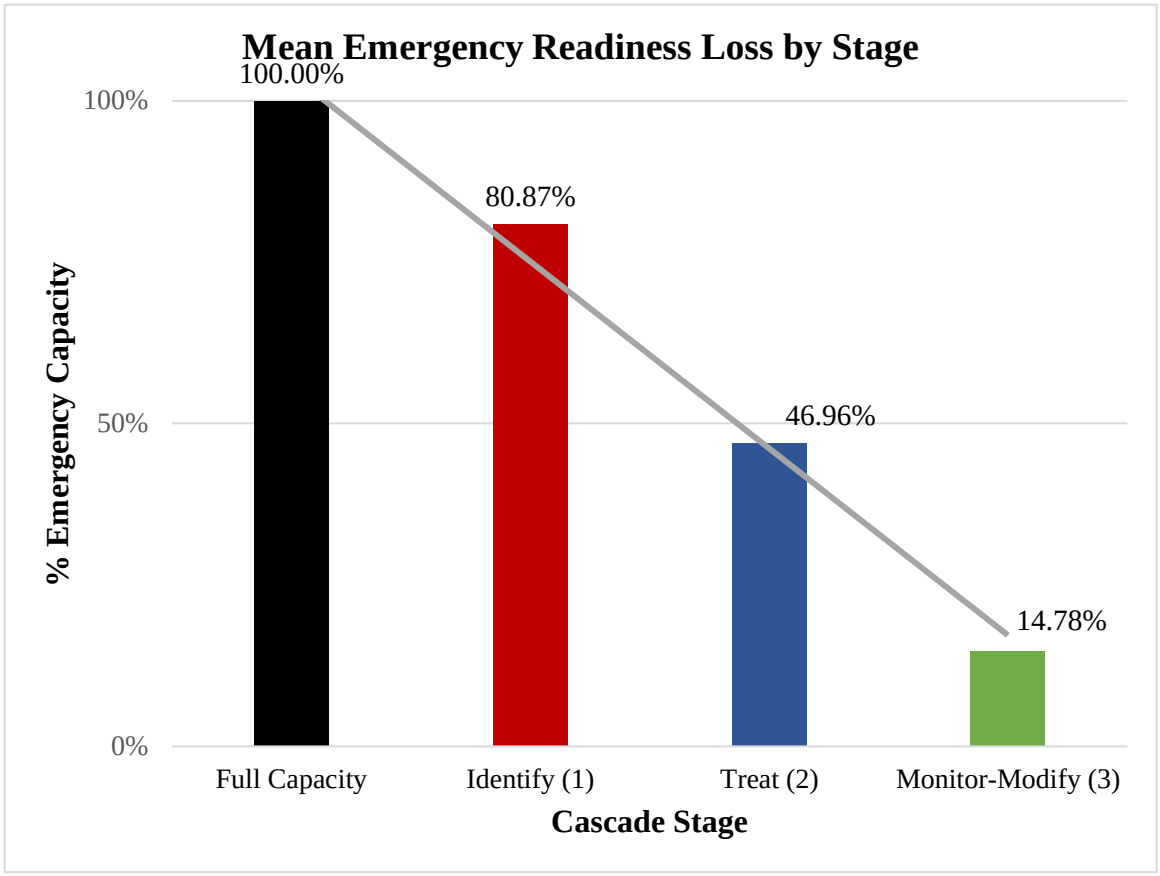

Figure 2. Mean Readiness Loss along the Clinical Cascade of Care

Table 6. Mean Readiness Loss by Cascade and Stage among All Facilities (1)

Readiness Loss by Stage				**Readiness Loss by Cascade**	
Loss by Clinical Cascade	**1**	**2**	**3**	***Mean Loss Across 3 Cascade Stages***	***SD***
	Identify	**Treat**	**Monitor-Modify**		
	--	--	--	**28.41%** [2]	**24.17** [3]
Sepsis-Infection	26.09%	26.09%	17.39%	23.19%	5.02
Hemorrhage	0.00%	39.13%	47.83%	28.99%	25.48
Hypertensive Emergency	69.57%	4.35%	13.04%	28.99%	35.41
Retained Placenta	0.00%	56.52%	34.78%	30.43%	28.51
Incomplete Abortion	0.00%	43.48%	47.83%	30.43%	26.45
Overall Loss by Stage					
Mean Loss Across Stage	**19.13%**	**33.91%**	**32.17%**		
SD	**30.37**	**19.78**	**16.44**	**3.01** [4]	

[1] n = 23 facilities
[2] Mean readiness loss across 3 clinical cascade stages and 5 emergency cascades
[3] Mean of the standard deviations
[4] Standard deviation across 3 stages and 5 emergency cascades

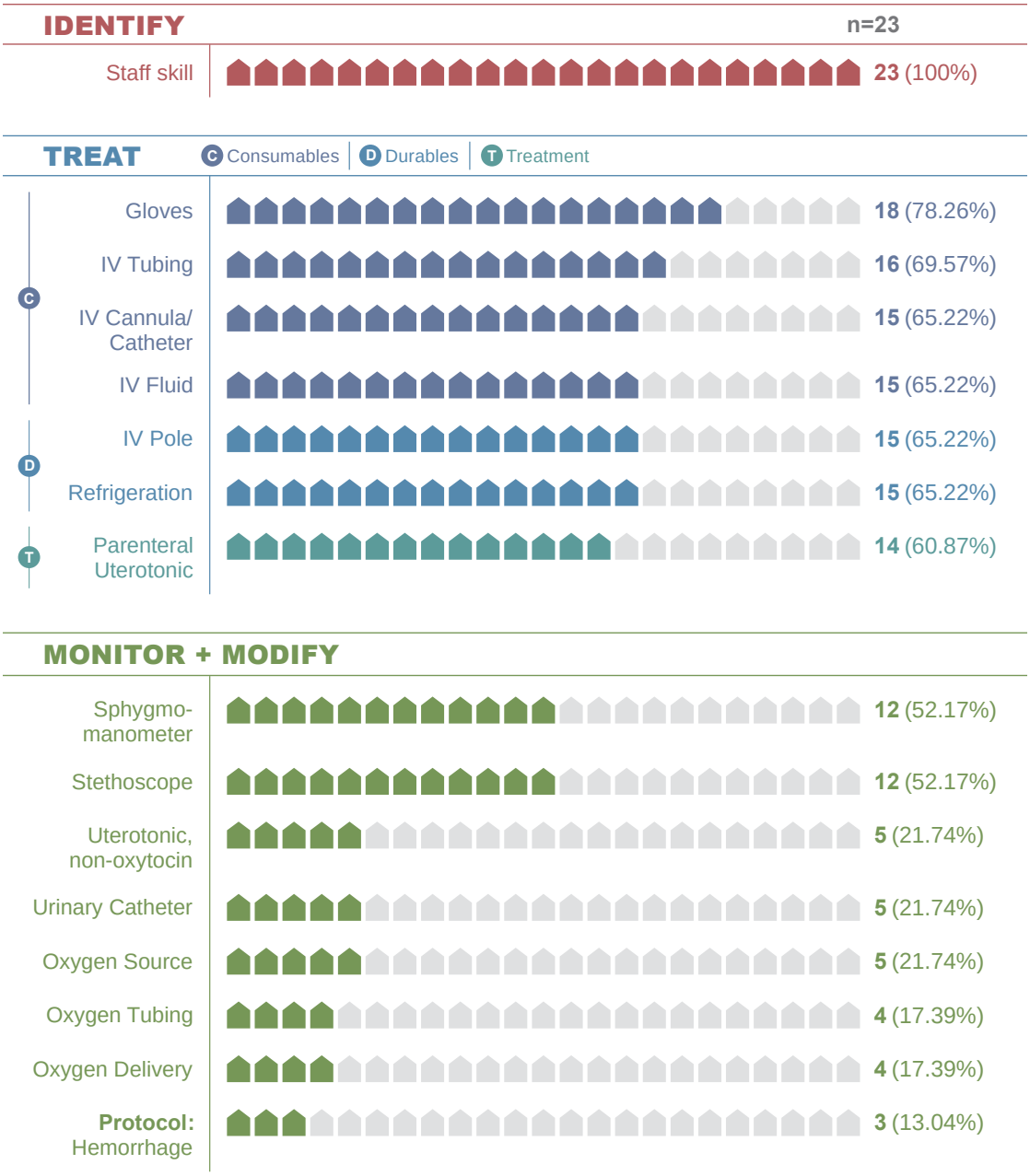

Figure 3. Hemorrhage Clinical Cascade

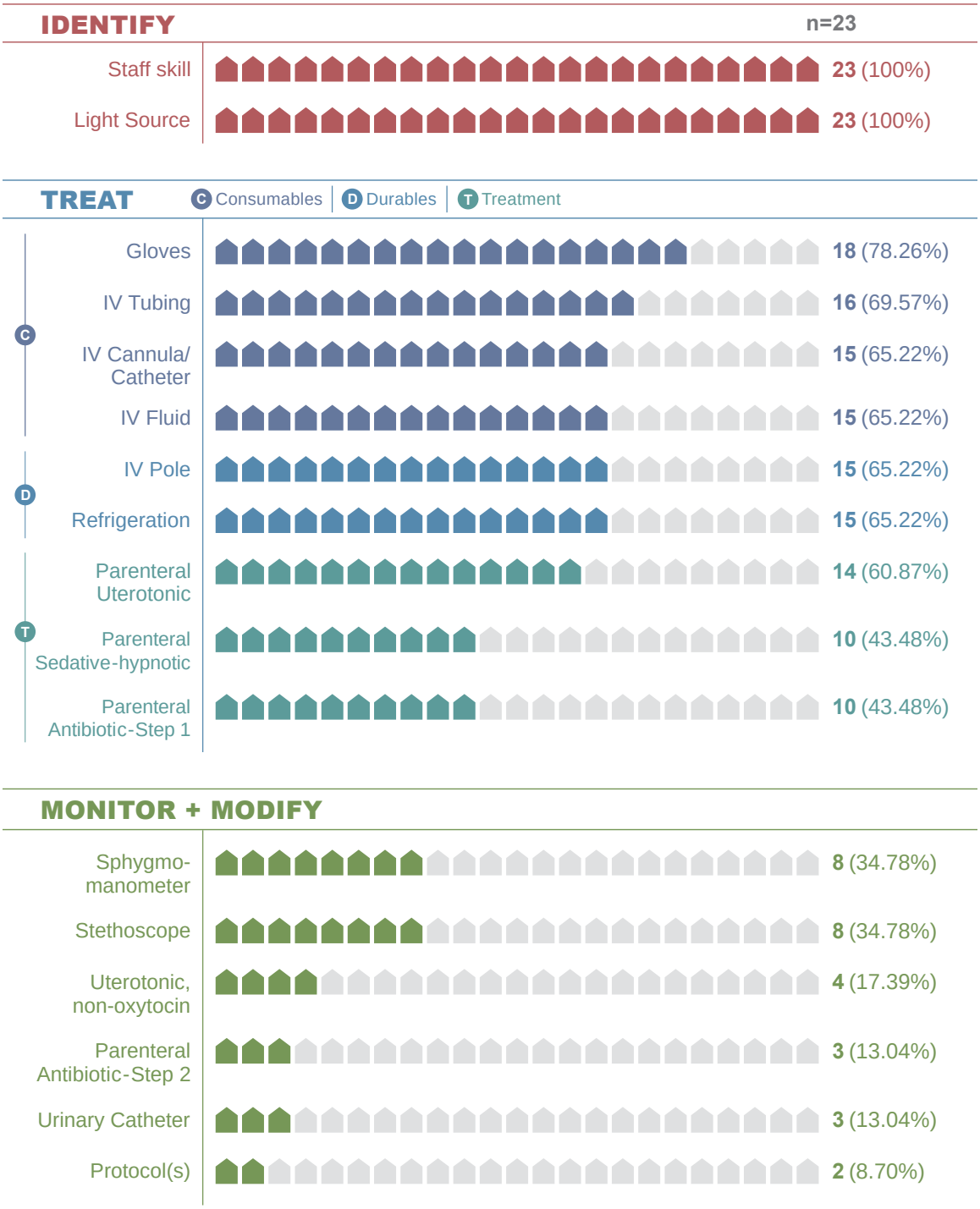

Figure 4. Retained Placenta Clinical Cascade

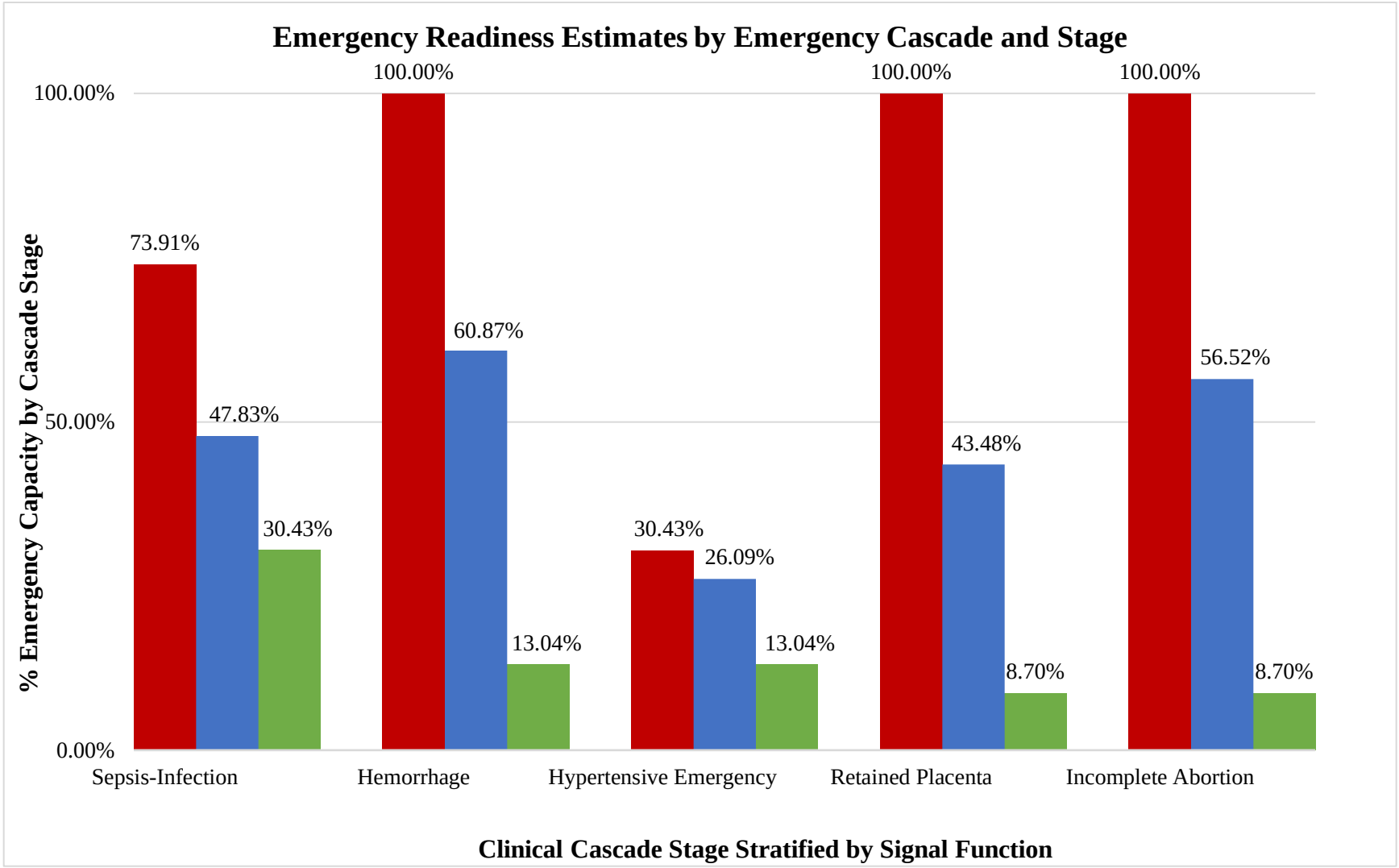

Figure 5. Emergency Readiness Estimates by Emergency Cascade and Stage

ONLINE SUPPLEMENTARY DOCUMENT

Table S 1. Facility Demographics

	%	**n** [(1)]
Country		
Kenya	73.91%	17
Uganda	26.09%	6
Level (ownership)		
Mission	17.39%	4
Government	82.61%	19
Regional Referral Hospital	*4.35%*	*1*
District Hospital	*13.04%*	*3*
County Referral Hospital	*4.35%*	*1*
Sub-County Hospital	*43.48%*	*10*
Health Center	*17.39%*	*4*
C-Section Capability		
Yes	43.48%	10
No	56.52%	13

(1) n = 23

Table S 2. Annual Delivery Volume

	Annual Total [1]	**Median** [2]	**25th**	**75th**	**IQR**
Kenya [3]	15,858.49	598.91	495.27	999.27	504.00
Uganda [4]	21,591.27	2,662.50	2,059.25	5,395.95	3,336.70
Total [5]	*37,449.76*	*994.50*	*537.27*	*1,808.64*	*1,271.36*

[1] Data was provided for up to 11 months in Kenya and up to 12 months in Uganda. To calculate the total annual delivery volume, we calculate the monthly average using the number of reported months for each individual facility and then multiplied that number by 12.
[2] The median and IQR are reported instead of the mean and standard deviation as the data are not normally distributed.
[3] n = 17
[4] n = 6
[5] n = 23

Table S 3. Consumable Supplies at Facilities

Category	**Sub-Category**	**Item**	**%**	**n** [1]
General Consumables	Testing	Urine Collection Cups	56.52	13
		Urine Dipsticks	56.52	13
	Procedures	IV Cannulas	86.96	20
		IV Tubing or Giving Set	86.96	20
		Urinary Catheters	82.61	19
	Personal Protection Equipment	Gloves (sterile or disposable latex)	78.26	18
Intravenous Fluids	First Line	IV Fluid	95.65	22

[1] n = 23

Table S 4. Durable Goods at Facilities

Category	Sub-Category	Item	%	n [1]
Delivery-Specific	Reusable	Manual Vacuum Aspirator Kit	86.96	20
General	Vital Signs	Thermometer	95.65	22
		Sphygmomanometer	91.30	21
		Stethoscope	82.61	19
	Physical Exam-Anthropometry	Flashlight	91.30	21
		Speculum	100.00	23
	Infrastructure	Power	100.00	23
		Oxygen Concentrator	78.26	18
		Oxygen Heads	39.13	9
		Oxygen Mask (Adult)	69.57	16
		Nasal Cannula	78.26	18
		Oxygen Cylinder	30.43	7
		Oxygen Tubing	69.57	16
	Other Instruments	IV Stand	95.65	22

[1] n = 23

Table S 5. Drugs at Facilities

Category	Sub-Category	Item	%	n [1]
Antibiotics	Penicillins	Ampicillin (injectable)	26.09	6
		Penicillin (any type)	86.96	20
	Cephalosporins	Cefotaxime or Ceftriaxone	56.52	13
	Aminoglycoside	Gentamicin (injectable)	78.26	18
Antihypertensive		Methyldopa	65.22	15
		Nifedipine	69.57	16
		Labetalol	13.04	3
Uterotonic		Oxytocin	91.30	21
		Ergometrine (IM)	4.35	1
		Misoprostol	34.78	8
Anti-Anxiety/Sedative		Diazepam (IV, for sedative purposes)	60.87	14
Anticonvulsant		Magnesium Sulfate (IV)	95.65	22
		Calcium Gluconate	52.17	12
		Hydralazine	73.91	17
Anesthetic		Lidocaine (for local anesthetic)	91.30	21

[1] n = 23

Table S 6. Guidelines and Protocols at Facilities

Category	Item	%	n
Guidelines	Antibiotic administration	26.09	6
	Eclampsia	43.48	10
	Management or treatment of obstetric hemorrhage	60.87	14
Protocol	Incomplete abortion	17.39	4
	Infection	43.48	10
	Puerperal Sepsis	17.39	4
	Retained Placenta	26.09	6

(1) n = 23

Table S 7. Comparison of Emergency Readiness Using Clinical Cascades and Signal Functions, Kenyan Facilities [1]

Clinical Cascade	**Signal Functions**	**Clinical Cascades**	**Overestimated Readiness**
(Signal Function)	**% Readiness, Tracer Items**	**% Readiness, Stage 2**	**[Signal Functions (-) Cascade]**
Medical Treatments			
Manage Sepsis - Infection *(Antibiotic)* [2]	64.71%	52.94%	11.76%
Manage Hemorrhage *(Oxytocic)* [3]	58.82%	58.82%	0.00%
Manage Hypertensive Emergency *(Anticonvulsant)* [4]	76.47%	23.53%	52.94%
Mean Medical Readiness	66.67%	45.10%	21.57%
Manual Procedures			
Manage Retained Placenta *(Manual removal of retained placenta)* [5]	70.59%	35.29%	35.29%
Manage Incomplete Abortion *(Manual removal of retained products of conception)* [6]	70.59%	58.82%	11.76%
Mean Manual Readiness	70.59%	47.06%	23.53%
	68.24%	**45.88%**	**22.35%**
Mean Overall Readiness:	*Signal Function Estimate*	*Cascade Estimate*	*% Overestimated by Signal Functions*

[1] n = 17 facilities

[2] IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin, and gentamicin or cefotaxime or ceftriaxone

[3] Gloves, IV fluids, IV cannula/catheter, IV tubing, oxytocin or misoprostol or ergometrine

[4] IV fluids, IV cannula/catheter, IV tubing, magnesium sulfate

[5] Flashlight or power, IV fluids, IV cannula/catheter, IV tubing, oxytocin, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone

[6] Flashlight or power, MVA kit, IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone

Table S 8. Comparison of Emergency Readiness Using Clinical Cascades and Signal Functions, Ugandan Facilities [1]

Clinical Cascade	**Signal Functions**	**Clinical Cascades**	**Overestimated Readiness**
(Signal Function)	**% Readiness, Tracer Items**	**% Readiness, Stage 2**	**[Signal Functions (-) Cascade]**
Medical Treatments			
Manage Sepsis – Infection *(Antibiotic)* [2]	83.33%	33.33%	50.00%
Manage Hemorrhage *(Oxytocic)* [3]	66.67%	66.67%	0.00%
Manage Hypertensive Emergency *(Anticonvulsant)* [4]	83.33%	33.33%	50.00%
Mean Medical Readiness	77.78%	44.44%	33.33%
Manual Procedures			
Manage Retained Placenta *(Manual removal of retained placenta)* [5]	66.67%	66.67%	0.00%
Manage Incomplete Abortion *(Manual removal of retained products of conception)* [6]	66.67%	50.00%	16.67%
Mean Manual Readiness	66.67%	58.33%	8.33%
Mean Overall Readiness:	**73.33%**	**50.00%**	**23.33%**

[1] n = 6 facilities
[2] IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin, and gentamicin or cefotaxime or ceftriaxone
[3] Gloves, IV fluids, IV cannula/catheter, IV tubing, oxytocin or misoprostol or ergometrine
[4] IV fluids, IV cannula/catheter, IV tubing, magnesium sulfate
[5] Flashlight or power, IV fluids, IV cannula/catheter, IV tubing, oxytocin, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone
[6] Flashlight or power, MVA kit, IV fluids, IV cannula/catheter, IV tubing, ampicillin or penicillin or gentamicin or cefotaxime or ceftriaxone

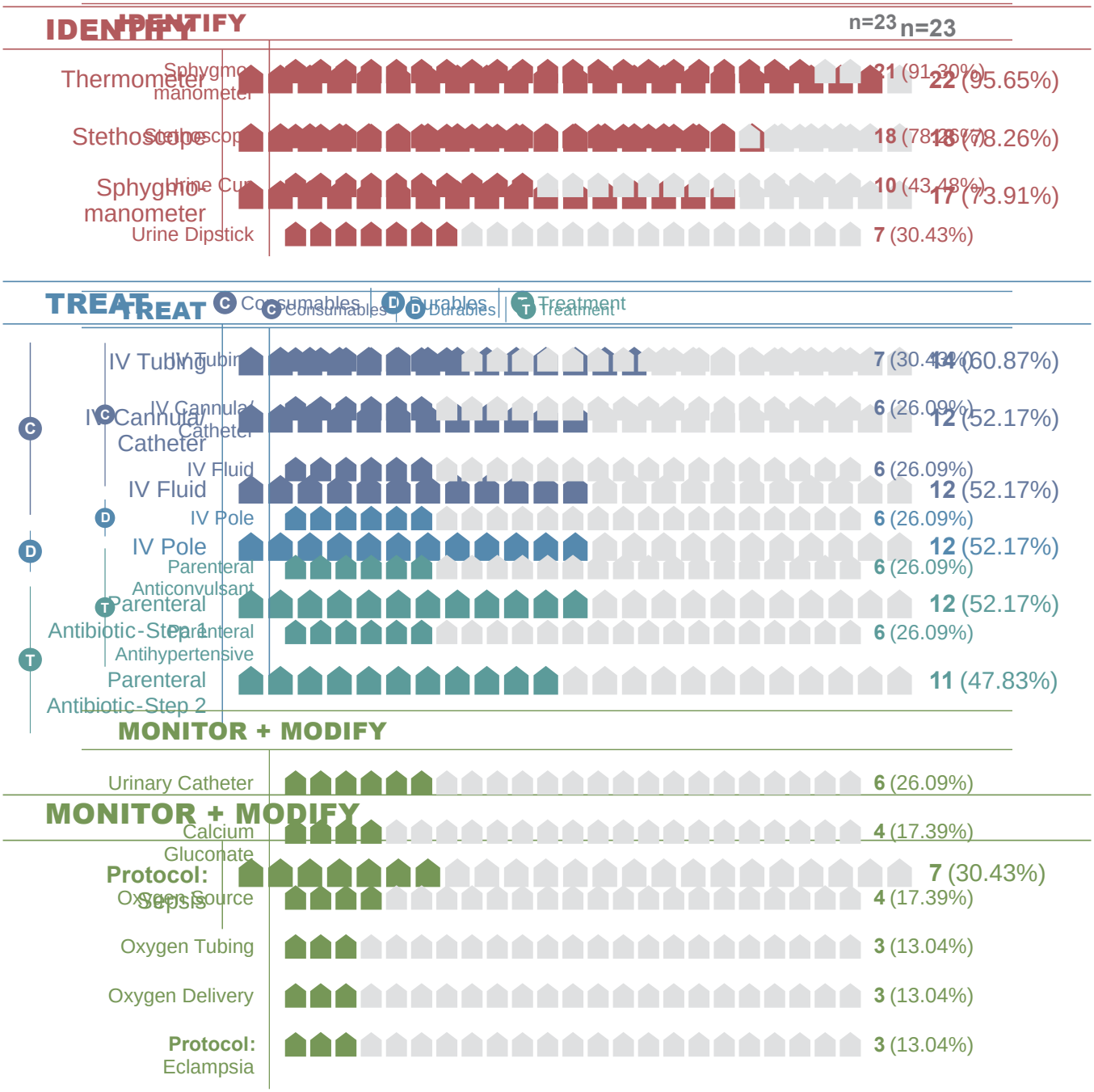

Figure S 2. Hypertensive Emergency Clinical Cascade

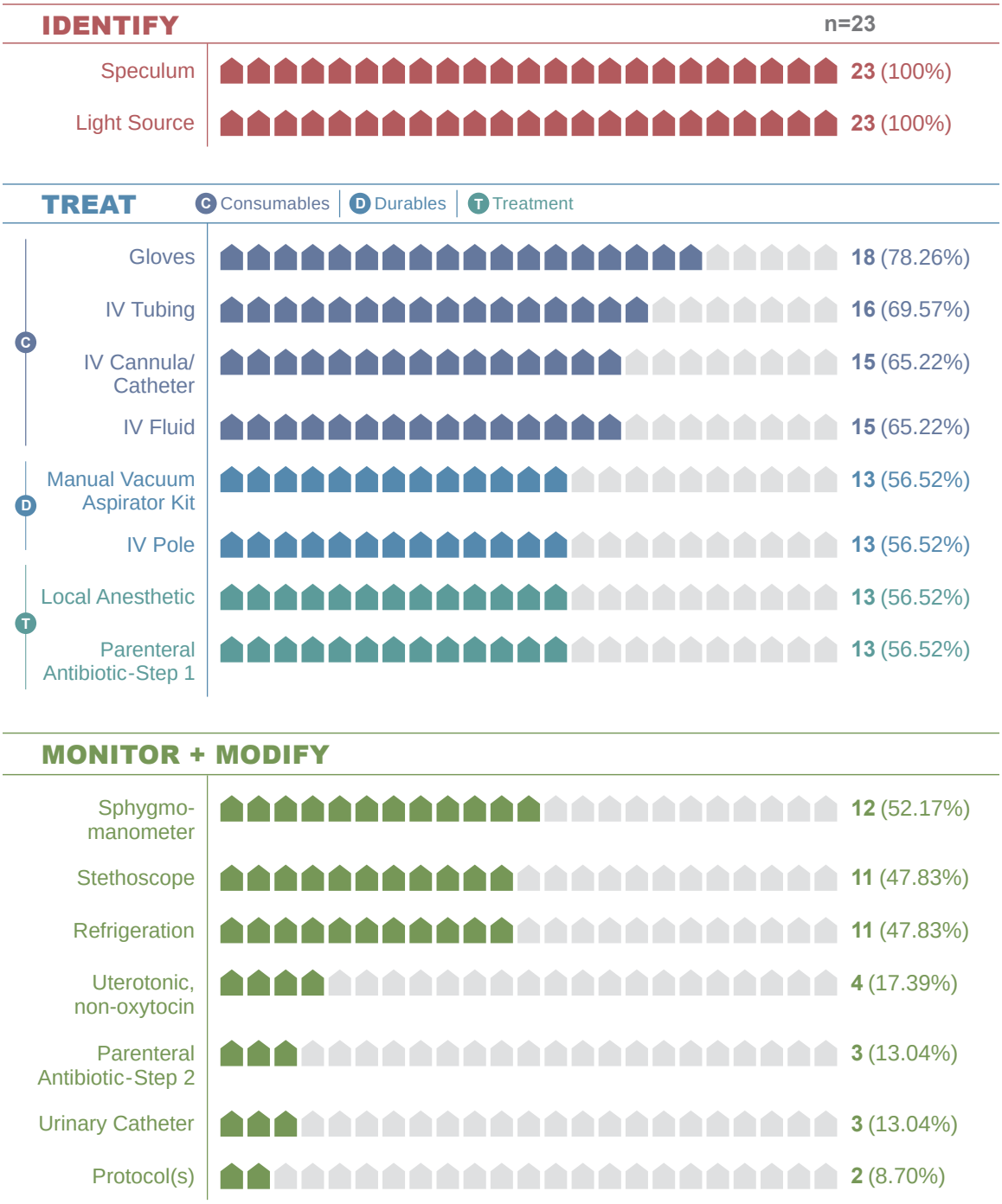

Figure S 3. Incomplete Abortion Clinical Cascade

Table S 9. Mean Readiness Loss by Cascade and Stage among Government Facilities [1]

	Readiness Loss by Stage			**Readiness Loss by Cascade**	
Loss by Clinical Cascade	**1**	**2**	**3**	***Mean Loss Across 3 Cascade Stages***	***SD***
	Identify	**Treat**	**Monitor-Modify**		
	--	--	--	**29.12%** [2]	24.71 [3]
Sepsis-Infection	26.32%	31.58%	21.05%	26.32%	5.26
Hemorrhage	0.00%	42.11%	42.11%	28.07%	24.31
Hypertensive Emergency	68.42%	5.26%	10.53%	28.07%	35.04
Retained Placenta	0.00%	63.16%	31.58%	31.58%	31.58
Incomplete Abortion	0.00%	47.37%	47.37%	31.58%	27.35
Overall Loss by Stage					
Mean Loss Across Stage	**18.95%**	**37.89%**	**30.53%**		
SD	**29.91**	**21.51**	**15.07**	**2.35** [4]	

[1] n = 19
[2] Mean readiness loss across 3 clinical cascade stages and 5 emergency cascades
[3] Mean of the standard deviations
[4] Standard deviation across 3 stages and 5 emergency cascades

Table S 10. Mean Readiness Loss by Cascade and Stage among Mission Facilities [1]

	Readiness Loss by Stage			**Readiness Loss by Cascade**	
Loss by Clinical Cascade	**1**	**2**	**3**	***Mean Loss Across 3 Cascade Stages***	***SD***
	Identify	**Treat**	**Monitor-Modify**		
	--	--	--	**25.00%** [2]	35.73 [3]
Sepsis-Infection	25.00%	0.00%	0.00%	8.33%	14.43
Hemorrhage	0.00%	0.00%	100.00%	33.33%	57.74
Hypertensive Emergency	75.00%	0.00%	25.00%	33.33%	38.19
Retained Placenta	0.00%	0.00%	75.00%	25.00%	43.30
Incomplete Abortion	0.00%	25.00%	50.00%	25.00%	25.00
Overall Loss by Stage					
Mean Loss Across Stage	**20.00%**	**5.00%**	**50.00%**		
SD	**32.60**	**11.18**	**39.53**	**10.21** [4]	

[1] n = 4
[2] Mean readiness loss across 3 clinical cascade stages and 5 emergency cascades
[3] Mean of the standard deviations
[4] Standard deviation across 3 stages and 5 emergency cascades

Table S 11. Mean Readiness Loss by Cascade and Stage among Referral Facilities [1, 2]

	Readiness Loss by Stage			Readiness Loss by Cascade	
Loss by Clinical Cascade	**1**	**2**	**3**	***Mean Loss Across 3 Cascade Stages***	***SD***
	Identify	**Treat**	**Monitor-Modify**		
	--	--	--	**22.22%** [3]	30.79 [4]
Sepsis-Infection	33.33%	0.00%	33.33%	22.22%	19.25
Hemorrhage	0.00%	0.00%	66.67%	22.22%	38.49
Hypertensive Emergency	33.33%	0.00%	33.33%	22.22%	19.25
Retained Placenta	0.00%	0.00%	66.67%	22.22%	38.49
Incomplete Abortion	0.00%	0.00%	66.67%	22.22%	38.49
Overall Loss by Stage					
Mean Loss Across Stage	**13.33%**	**0.00%**	**53.33%**		
SD	**18.26**	**0.00**	**18.26**	**0.00** [5]	

[1] n = 3
[2] One of the 3 facilities included in the sample is not a referral facility based on country designation, but serves as a referral facility, in practice, based on proximity to the road and the next closest referral facility. This determination was made in consultation with the in-country research team.
[3] Mean readiness loss across 3 clinical cascade stages and 5 emergency cascades
[4] Mean of the standard deviations
[5] Standard deviation across 3 stages and 5 emergency cascades

Table S 12. Mean Readiness Loss by Cascade and Stage among Kenyan Government Facilities [(1)]

	Readiness Loss by Stage			**Readiness Loss by Cascade**	
Loss by Clinical Cascade	**1**	**2**	**3**	***Mean Loss Across 3 Cascade Stages***	***SD***
	Identify	**Treat**	**Monitor-Modify**		
				28.00% [(2)]	27.43 [(3)]
Sepsis-Infection	20.00%	33.33%	20.00%	24.44%	7.70
Hemorrhage	0.00%	46.67%	33.33%	26.67%	24.04
Hypertensive Emergency	73.33%	0.00%	6.67%	26.67%	40.55
Retained Placenta	0.00%	73.33%	20.00%	31.11%	37.91
Incomplete Abortion	0.00%	46.67%	46.67%	31.11%	26.94
Overall Loss by Stage					
Mean Loss Across Stage	**18.67%**	**40.00%**	**25.33%**		
SD	**31.76**	**26.67**	**15.20**	**2.98** [(4)]	

[(1)] n = 15
[(2)] Mean readiness loss across 3 clinical cascade stages and 5 emergency cascades
[(3)] Mean of the standard deviations
[(4)] Standard deviation across 3 stages and 5 emergency cascades

Table S 13. Mean Readiness Loss by Cascade and Stage among Ugandan Government Facilities [1]

	Readiness Loss by Stage			**Readiness Loss by Cascade**	
Loss by Clinical Cascade	**1**	**2**	**3**	***Mean Loss Across 3 Cascade Stages***	***SD***
	Identify	**Treat**	**Monitor-Modify**		
				33.33% [2]	26.82 [3]
Sepsis-Infection	50.00%	25.00%	25.00%	33.33%	14.43
Hemorrhage	0.00%	25.00%	75.00%	33.33%	38.19
Hypertensive Emergency	50.00%	25.00%	25.00%	33.33%	14.43
Retained Placenta	0.00%	25.00%	75.00%	33.33%	38.19
Incomplete Abortion	0.00%	50.00%	50.00%	33.33%	28.87
Overall Loss by Stage					
Mean Loss Across Stage	**20.00%**	**30.00%**	**50.00%**		
SD	**27.39**	**11.18**	**25.00**	**0.00** [4]	

[1] n = 4
[2] Mean readiness loss across 3 clinical cascade stages and 5 emergency cascades
[3] Mean of the standard deviations
[4] Standard deviation across 3 stages and 5 emergency cascades

Table S 14. Mean Readiness Loss by Cascade and Stage among Facilities with Reported C-Section Capability [1]

	Readiness Loss by Stage			**Readiness Loss by Cascade**	
Loss by Clinical Cascade	**1**	**2**	**3**	***Mean Loss Across 3 Cascade Stages***	***SD***
	Identify	**Treat**	**Monitor-Modify**		
	--	--	--	**26.67%** [2]	24.82 [3]
Sepsis-Infection	40.00%	10.00%	10.00%	20.00%	17.32
Hemorrhage	0.00%	30.00%	60.00%	30.00%	30.00
Hypertensive Emergency	60.00%	10.00%	20.00%	30.00%	26.46
Retained Placenta	0.00%	30.00%	50.00%	26.67%	25.17
Incomplete Abortion	0.00%	30.00%	50.00%	26.67%	25.17
Overall Loss by Stage					
Mean Loss Across Stage	**20.00%**	**22.00%**	**38.00%**		
SD	**28.28**	**10.95**	**21.68**	**4.08** [4]	

[1] n = 10
[2] Mean readiness loss across 3 clinical cascade stages and 5 emergency cascades
[3] Mean of the standard deviations
[4] Standard deviation across 3 stages and 5 emergency cascades

Table S 15. Mean Readiness Loss by Cascade and Stage among Facilities without Reported C-Section Capability [1]

	Readiness Loss by Stage			**Readiness Loss by Cascade**	
Loss by Clinical Cascade	**1**	**2**	**3**	***Mean Loss Across 3 Cascade Stages***	***SD***
	Identify	**Treat**	**Monitor-Modify**		
	--	--	--	**29.74%** [2]	29.49 [3]
Sepsis-Infection	15.38%	38.46%	23.08%	25.64%	11.75
Hemorrhage	0.00%	46.15%	38.46%	28.21%	24.73
Hypertensive Emergency	76.92%	0.00%	7.69%	28.21%	42.37
Retained Placenta	0.00%	76.92%	23.08%	33.33%	39.47
Incomplete Abortion	0.00%	53.85%	46.15%	33.33%	29.12
Overall Loss by Stage					
Mean Loss Across Stage	**18.46%**	**43.08%**	**27.69%**		
SD	**33.35**	**28.05**	**15.00**	**3.44** [4]	

[1] n = 13
[2] Mean readiness loss across 3 clinical cascade stages and 5 emergency cascades
[3] Mean of the standard deviations
[4] Standard deviation across 3 stages and 5 emergency cascades

Table S 16. Clinical Cascade Readiness Estimates Tests of Significance

Clinical Cascade	**Clinical Cascade Stage**	**Level of Care p-value** [(1)] *(C-section Capability vs. No C-section Capability)*	**Level of Care p-value** [(2)] *(Referral vs Non)*	**Ownership p-value** [(3)] *(Mission vs. Government)*	**Country p-value** [(4)] *(Kenya vs. Uganda)*
Sepsis-Infection	Stage 2	1.00	0.59	0.32	0.64
	Stage 3	0.65	1.00	0.07	0.62
Hemorrhage	Stage 2	0.67	0.25	0.13	1.00
	Stage 3	1.00	0.36	1.00	0.54
Hypertensive Emergencies	Stage 2	1.00	0.16	1.00	0.63
	Stage 3	1.00	0.36	1.00	0.54
Retained Placenta	Stage 2	0.04*	0.07	0.02*	0.34
	Stage 3	0.18	0.25	0.32	0.46
Incomplete Abortion	Stage 2	0.40	0.23	0.60	1.00
	Stage 3	0.18	0.25	0.32	0.46

*P<0.05
[(1)] C-section: n = 10
[(2)] Referral: n = 3
[(3)] Mission: n = 4
[(4)] Kenya: n = 17

CHAPTER 5: PUBLIC HEALTH IMPLICATIONS

Building off of the wealth of research on the signal functions and the formative research on clinical cascades, this study was designed to assess emergency readiness by comparing the signal functions to the novel clinical cascade approach at facilities in two East African countries. More specifically, this study aimed to: (1) compare estimates of facility readiness to manage common obstetric emergencies using clinical cascades and signal functions, (2) compare these estimates between countries and levels of care, and (3) test the cascading loss of emergency obstetric resources. This study provides the first-ever multi-country comparison of the signal functions and clinical cascades estimates of obstetric emergency readiness. This study has important implications for future research, the measurement of emergency readiness, and facility and health system interventions. Specifically, these findings support the need for (1) additional research in diverse settings and across levels of the health system, (2) reconsidering how we measure emergency readiness, and (3) targeted facility or health system interventions to improve readiness to handle the five leading causes of global maternal mortality.

In comparing the signal function and clinical cascade estimates of readiness, we found four important findings. First, in line with the one previously published comparison of the two methods, findings from this study indicated that signal functions overestimate practical obstetric emergency readiness (mean of 22.61% overestimation across emergencies found in our study). This finding suggests that fewer facilities in Kenya and Uganda are prepared to handle obstetric emergencies than originally determined by the signal functions, and also adds to the mounting concerns regarding the accuracy of the signal functions as a measure of emergency readiness. Second, in expanding upon the previously published comparison of the signal function and novel clinical cascade models, our study examined the overestimation between CEmOC and BEmOC facilities. We found that, based on both clinical cascade and signal function estimates, not all comprehensive emergency obstetric care facilities were ready to perform basic emergency

obstetric care, with an estimated readiness of 58.00% and 80.00%, respectively, across the five clinical cascades and signal functions. This suggests that CEmOC facilities are not equipped to handle the level of care that their facility designation requires. Third, as expected, we saw a consistent pattern of reduction in readiness across the clinical cascade of care for all emergencies, with very few facilities (46.96%, on average) equipped to identify and treat the leading causes of maternal death. Fourth, across the five emergencies and three stages of care, we saw a consistent pattern of 28.41% readiness loss (SD = 3.01). The largest drop off in readiness took place when treating the emergency (33.91% loss of readiness on average); however, there was substantial variability in loss at each stage by emergency. This pattern of readiness loss was remarkably similar to that found in a previous study of 44 BEmOC facilities in Kenya (33.03%) and a study of the clinical cascades as applied to neonatal emergencies among the 23 facilities included in our study (30.00%) [22,25]. Together, these three studies suggest a consistent readiness loss of approximately 30% across emergencies and stages in both maternal and neonatal contexts.

Given the limitations of our study and the dearth of previously published literature, there is demand for future research. Firstly, the data used in this study were collected at a single point in time, offering a cross-sectional view of readiness at select facilities. Given the erratic availability of consumable resources and drugs, a single timepoint may be insufficient to capture a complete picture of readiness. Collecting data from the same set of facilities at more frequent intervals could not only provide more accurate readiness data, but also point to patterns in availability based on supply procurement timelines. Secondly, future studies could collect information on resource functionality (e.g. drug expiration dates), facility staffing levels, and clinician knowledge and skillset to allow for a more precise estimate of readiness. Thirdly, though available in the original dataset, our analysis did not account for the location of resources. As such, though our research described whether resources were available at the facility, we could not determine how easily accessible they are during an emergency. Given the importance of time in an emergency, this factor is critical and should be explored in future research. Lastly, future

research should link cascade estimates of readiness to facilities' adverse clinical outcomes (e.g., mortality as measured by MMR; maternal near miss as measured by Maternal Near Miss Ratio, or severe maternal outcomes, as measured by Severe Maternal Outcomes Ratio).

Beyond the implications for future research, our study contributes to the emerging evidence on the clinical cascades as a preferred alternative to the signal functions in measuring emergency readiness. Together with the two previously published studies, our research adds to the mounting concerns regarding the accuracy of the signal functions as an indicator of clinical obstetric emergency readiness. By defining the resources necessary to identify and treat emergencies and monitor and modify treatment as clinically indicated, the cascades provide a detailed, stepwise analysis of resource availability and a novel set of readiness indicators (practical emergency readiness, readiness loss by stage of clinical care, aggregate readiness loss across all stages of care, and readiness loss by stage). Cascade findings allow us to see precisely where readiness is lost, at the individual resource level. Measuring readiness according to the clinical cascades requires a marginal increase in effort during data collection but provides a more nuanced picture of clinical care. Given the comprehensiveness of the cascade system of measurement, and the preference to under- versus over-estimate readiness, the field should consider shifting away from the traditionally used signal function measurement and towards the novel clinical cascades.

Lastly, our detailed analysis of a facility's readiness to handle obstetric emergencies may be used to guide emergency-specific or supply-specific interventions to close gaps in emergency supplies at Kenyan and Ugandan facilities. Real-time or demand-based requests for strategic emergency supplies may close gaps in supply availability and strengthen systems' capacity to successfully manage labor-related emergencies at individual facilities or across health system networks. For instance, our cascade findings can be used to prioritize the procurement of high-yield consumable supplies, durable goods, and drugs that are used across the widest array of emergencies. Moreover, our stratified estimations of readiness among CEmOC compared to

BEmOC facilities, suggest a need for additional investment in CEmOC facilities in order to equip them to handle the full range of emergency obstetric care. Broadly, our findings support the need for targeted facility or health system interventions in Kenya and Uganda to improve readiness to handle the five leading causes of global maternal mortality.

In conclusion, emergency obstetric care is critical in managing the obstetric complications driving elevated maternal mortality ratios in Sub-Saharan Africa, therefore requiring an accurate measurement of readiness to handle such complications. In line with previously published research, our study suggests the need to reconsider the signal functions as the preferred method of measuring readiness. Measuring readiness according to the clinical cascades requires a marginal increase in effort during data collection but provides a more nuanced picture of clinical care that can be used to guide strategies that optimize emergency commodity provision and strengthen system-level strategies for emergency-specific maternal survival.

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