Pulse oximetry in low-income settings:

a case study of Kenyan hospitals

A thesis submitted to the University of Oxford

for the degree of Doctor of Philosophy

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St Edmund Hall

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Abstract

Pulse oximeters are low-cost, easy to use, and effective at detecting hypoxemia (low blood oxygen levels), a common complication of bronchiolitis, asthma, and pneumonia, the leading infectious cause of death in children worldwide. However, pulse oximeters are often unavailable in low-income settings, and if available, often underused, yet little research investigates why.

In this thesis, I examine pulse oximeter implementation in low-income settings, focusing on Kenyan hospitals as a case study, and using a mixed-methods approach. I conducted a systematic literature review, examining how pulse oximeter use with children at admission to hospital impacts health outcomes; I then conducted quantitative analyses of 28,000 children admitted to seven Kenyan hospitals to determine with which children pulse oximeters are used, and pulse oximetry's impact on treatment provision; these analyses informed the qualitative research component, for which I conducted interviews with 30 healthcare workers (HCWs) and staff in 14 Kenyan hospitals and employed theoretical frameworks to determine how HCWs decide whether to use pulse oximeters, and the barriers to pulse oximetry.

I found that pulse oximeter use varies substantially between and within Kenyan hospitals over time. After adjusting for case-mix and signs of illness severity, HCWs were most likely to use pulse oximeters with children with a very high respiratory rate, indrawing and/or who were not alert; children who obtained a pulse oximeter reading were more likely to be prescribed oxygen than if a pulse oximeter was not used; and children with a reading below 90% were more likely to be prescribed oxygen than those with higher readings, suggesting that HCW decision-making is influenced by international and national guidelines. However, HCWs sometimes cannot use pulse oximeters when they intend to, because of insufficient pulse oximeter availability, largely due to inefficient and confusing procurement processes and repair delays. Furthermore, HCWs sometimes use pulse oximeters incorrectly or misinterpret their results, because of insufficient training.

Pulse oximeter promotion programme planners can use the recommendations I provide to effectively target barriers to pulse oximeter uptake in low-income settings. Increased pulse oximetry implementation could enable early detection of hypoxemia, improving accurate diagnosis, and supporting prompt, effective treatment, which could help reduce mortality in children needing oxygen, in line with Sustainable Development Goal 3.

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List of acronyms

AIC	Akaike information criterion
CIN	Clinical Information Network
CMEs	Continuing Medical Education Sessions
CO / COI	Clinical Officer / Clinical Officer Intern
CFIR	Consolidated Framework for Implementation Research
CUREC	Oxford University's Central University Research Ethics Committee
ED	Emergency Department
HCW / HCWs	Healthcare worker / healthcare workers
GVIF	Generalized Variable Inflation Factor
IMBP	Integrative Model of Behavioural Prediction
KEMRI	Kenya Medical Research Institute
KWTRP	Kenya Wellcome Trust Research Programme
MO / MOI	Medical Officer / Medical Officer Intern
MAR	Missing at Random
MCAR	Missing Completely At Random
MICE	Multivariate Imputation by Chained Equations
MoH	Ministry of Health
MNAR	Missing Not At Random
OXTREC	Oxford Tropical Research Ethics Committee
PAR	Paediatric Admissions Record
SaO2	Oxygen saturation
SDGs	Sustainable Development Goals
SERU	KEMRI's Scientific and Ethics Review Unit
SpO2	Peripheral oxygen saturation
TB	Tuberculosis
TDF	Theoretical Domains Framework
UN	United Nations
USAID	United States Agency for International Development
WHO	World Health Organization

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Chapter 1: Introduction, diffusion of innovation background, and structure of thesis

1.1 Introduction

1.1.1 International initiatives to promote uptake of effective low-cost interventions

The United Nations' Sustainable Development Goals (SDGs) were adopted in 2015, and expand on the Millennium Development Goals by emphasising economic, environmental and social development. The SDGs provide a detailed set of targets for each goal, and the 17 goals provide a framework, objectives, and metrics "*to end poverty, protect the planet, and ensure prosperity for all*".[United Nations,2015; United Nations,2017] SDG 3 focuses on "*ensur(ing) healthy lives and promot(ing) well-being for all at all ages*". One of its targets is:

> "B*y 2030 (to) end preventable deaths of newborns and children under 5 years of age, with all countries aiming to reduce (…) under-5 mortality to at least as low as 25 per 1,000 live births*".[United Nations,2017]

In 2016, 5.6 million children aged under five died. The global average under-5 mortality rate was 41 deaths per 1,000 live births, but in low-income countries the average was 73, and several low-income countries had more than 120 deaths per 1,000 live births.[WHO,2017a; WHO,2017b; World Bank,2017]

While cost limits adoption of many interventions with the capacity to improve child health outcomes, there is scope to improve outcomes through the implementation of low-cost, effective interventions. The World Health Organization (WHO) reports that "*more than half of these early child deaths are due to conditions that could be prevented or treated with access to simple,*

affordable interventions".[WHO,2017a] This has been recognised by a number of international organisations and global health partnerships. Thus, the Global Strategy for Women's, Children's and Adolescent's Health 2016-2030, created through a stakeholders' partnership headed by the WHO, states:

> "*We must maximize the impact of investment by integrating efforts across diseases and sectors, by using innovative, cost-effective and evidence-based tools and approaches, and by making financing channels more effective*."[Every Woman Every Child,2015]

Similarly, USAID's Global Health Strategic Framework 2012-2016 states:

> "*To protect children in the first five years of life, USAID will increasingly rely on low-cost, easy-to-use interventions that achieve highest impact by preventing and treating the leading causes of child death: pneumonia, diarrhoea, prematurity, asphyxia, malaria and newborn sepsis*."[USAID,2012b]

Furthermore, The Gates Foundation's Global Health Program Overview publication states that their Maternal, Neonatal and Child Health program's strategy is:

> "*to reduce the number of mothers and newborns who die during and immediately after birth by developing and introducing low-cost, easy-to-use tools, technologies, and treatments for the major causes of these deaths*".[Bill&Melinda Gates Foundation,2010]

However, there are many examples of low-cost interventions not being implemented at scale. Malkin(2007) describes how past international efforts to increase access in low-income countries to effective low-cost health technologies such as oral rehydration solutions for diarrhoea, antibiotics, vector control agents for malaria, and latrines were largely unsuccessful, because of issues such as insufficient training, inadequate infrastructure, mistrust of leaders, and unavailability of spare parts or consumables. More broadly the WHO states that "*Despite abundant evidence of the efficacy of affordable, life-saving interventions, there is little understanding of how to deliver those interventions effectively in diverse settings and within the wide range of existing health systems. Implementation issues often arise as a result of contextual factors that policy-makers and health*

system managers may not even have considered."[Peters et.al.2013] Such issues will be described in more detail in Section 1.2.

1.1.2 Pulse oximeters – an effective low-cost intervention

One example of an easy-to-use, effective, low-cost technology that improves health outcomes is the pulse oximeter, which detects hypoxemia (low blood oxygen levels) in children.[WHO,2014b] Hypoxemia is associated with increased risk of death in children and adolescents, and is a common complication of pneumonia, bronchiolitis, asthma and other serious conditions (e.g. sepsis).[WHO,2014b; Lozano,2001; Djelantik et.al.2003; Orimadegun et.al.2014] Evidence suggests pulse oximeters identify 20-30% additional hypoxic children compared with using clinical signs alone, e.g. grunting and depressed consciousness, which can be imprecise.[WHO,2014b; Hanning&Alexander-Williams,1995] Floyd et.al.(2015) estimated that introducing pulse oximeters into 15 low-income countries with the highest burden of severe pneumonia could prevent 148,000 annual pneumonia deaths. Thus, widespread pulse oximetry implementation could help reduce mortality in children needing oxygen, in line with Sustainable Development Goal 3, by enabling early detection of hypoxemia, improving accurate diagnosis, and supporting prompt, effective treatment. Box 1.1 describes pulse oximeters' characteristics, and Appendix 1.1 displays diagrams and images of a range of pulse oximeters e.g. hand-held forms vs. those with table-top or standalone monitors.

Box 1.1: Characteristics of pulse oximeters:

- Pulse oximeters consist of a probe, placed most commonly on the finger in adults and children, or the toe or ear in babies, and a monitor.

- Oxygenated haemoglobin absorbs more light in the red spectrum compared to de-oxygenated haemoglobin, while de-oxygenated haemoglobin absorbs more light in the infrared spectrum than oxygenated haemoglobin. Therefore light in the red and infrared spectrums are passed between the two sides of the probe; by monitoring the light absorption levels, pulse oximeters determine the person's arterial haemoglobin oxygen saturation level.[Fouzas et.al.2011]

- Various pulse oximeters are available, with a range of designs and costs. Digit oximeters for personal use are available for $35-400, hand-held oximeters cost around $60-1200, while hospital pulse oximeters with standalone monitors generally cost $800-4500.[WHO,2012]

- A pulse oximeter's lifespan will likely vary by type and location (e.g. use frequency, healthcare worker training). Weber&Mulholland(1998) found that pulse oximeters that were used for 5,000-10,000 readings per year per machine in three Gambian hospitals over seven years broke roughly every 2-3 years, and probes needed replacement around every 6 months. When Gray et.al.(2017) introduced pulse oximeters into 20 district hospitals in Laos, no pulse oximeters had broken after one year; after two years, 90% of the pulse oximeters (if considered distinctly from their probes) were working, as were most of the probes; and after three years, 30% of pulse oximeters had broken, as had 0-100% of the probes depending on the hospital.

- Pulse oximeters are on average accurate to +/- 2% [Jensen et.al.1998] Information is variable on whether pulse oximeters require recalibration after use in healthcare settings: the WHO says pulse oximeters self-calibrate [WHO,2011b], while Ingram&Munro(2005) state that they require recalibration after 3 years, and Milner &Mathews(2012) argue "*Once in use, there is little evidence that pulse oximeters are ever re-calibrated or have their accuracy assessed*".

1.1.3 Hypoxemia: the burden and its implications for child mortality rates

Pulse oximetry has the potential to improve health outcomes in the context of a high prevalence of hypoxemia, and its association with an increased risk of death. It has been estimated that a median

of 13% of children with severe or very severe pneumonia have hypoxemia.[Subhi et.al.2009a] Junge et.al.(2006) found that hypoxemia prevalence in hospitalized Gambian children varied by diagnosis, with an average of 6% of all admitted children; in children with acute lower respiratory infections hypoxemia was present in 12%, in 17% of neonates, 3% of those with malaria (and 7% of those with cerebral malaria), and 3% of those with meningitis.

Having insufficient blood oxygenation leads to insufficient tissue oxygenation, which can rapidly cause organ dysfunction and death.[WHO,2014b] Lozano's systematic review of 17 studies reported that the risk of death in hypoxic children under 5 with acute lower respiratory infections in Kenya, the Gambia and Zambia was 1.4-4.6 times higher than in those without hypoxemia [Lozano,2001]; and Orimadegun et.al.(2014) found that hypoxemia was a predictor of death in Nigerian children under 5 with severe malaria (AOR 7.54). In Mwaniki et.al.(2009)'s study conducted in Kenya, 6% (753/13,183) of all children aged over two months died, compared with 22% (150/693) of those with hypoxemia.

Of the conditions for which hypoxemia is a common complication, pneumonia has a particularly high burden and poor outcomes. Two thirds of children with pneumonia do not obtain necessary antibiotics, and pneumonia is the leading infectious cause of death in children under five worldwide, causing almost one million under five deaths in 2015.[WHO,2016b; Liu et.al.2016] In detecting hypoxemia, pulse oximetry could help diagnose, determine illness severity, and ascertain appropriate treatment for these children with pneumonia and other hypoxemia-related conditions. National and international health organisations are becoming increasingly aware of these possibilities, as evidenced by their recommendations and guidelines.

1.1.4 Recognition of the importance of pulse oximetry for assessing children

A wide range of guidelines on care for children recommend pulse oximetry to assess children presenting to health facilities.

Thus, the WHO's 2012 Recommendations for Management of Common Childhood Conditions states:

> *"Pulse oximetry is recommended to determine the presence of hypoxaemia and to guide administration of oxygen therapy in infants and children with hypoxaemia".* This is classified as a "strong recommendation".[WHO,2012]

The British Thoracic Society's 2011 Guidelines for the Management of Community Acquired Pneumonia in Children claims:

> *Pulse oximetry is one of the "general investigations (that) should be done in a child with CAP (community-acquired pneumonia) who comes to hospital."*[Clark et.al.2011]

The Clinical Practice Guidelines of the Pediatric Infectious Diseases Society and the Infectious Diseases Society of America states:

> "*Pulse oximetry should be performed in all children with pneumonia and suspected hypoxemia. The presence of hypoxemia should guide decisions regarding site of care and further diagnostic testing.*"[Bradley et.al.2011]

Furthermore, the Scottish Intercollegiate Guidelines Network (SIGN)'s 2014 British Guideline on the Management of Asthma argues:

> *"Accurate measurements of oxygen saturation are essential in the assessment of all children with acute wheezing. Oxygen saturation monitors should be available for use by all health professionals assessing acute asthma in both primary and secondary care settings."*[Healthcare Improvement Scotland,2014]

The international non-profit PATH published a report in 2015 that describes 10 effective low-cost interventions that if implemented could reduce the number of deaths in children and mothers by a million in one year; one of these is a pulse oximeter adapted for use with smartphones.[PATH,2015]

1.1.5 Availability and use of pulse oximeters

Despite the potential to improve health outcomes, and the widespread recognition of their importance, pulse oximeters are often not available, particularly in low-income settings. For example, only 38% of Nigerian tertiary hospitals and three of 22 Kenyan hospitals providing physician internship training had pulse oximeters in 2011 and 2012 respectively.[Desalu et.al.2011; English et.al.2014]

To promote access, pulse oximeters have been designed for low-income settings, e.g. Lifebox, a low-cost, robust, portable, battery-operated oximeter.[Lifebox,2015] Other designs, including but not limited to the aforementioned Phone Oximeter, deliver pulse oximeter results to smartphones, utilizing their spread to remote areas; and others attempt to circumvent unreliable access to electricity by employing other sources of power, e.g. manual winding, solar power, or body heat.[Peterson et.al.2013; WHO,2015; Ostfeld et.al.2016; Torfs et.al.2006] Recognizing the importance of pulse oximeters, various international initiatives aim to support pulse oximeter uptake in low-income countries, including the WHO's Global Pulse Oximetry Project, Lifebox donations, and the BMJ Christmas Appeal. [Lifebox,2015; WHO,2008; Feinmann,2011]

However, studies have found that even when pulse oximeters are available, they are often not used.[McCollum et.al.2013; Ginsburg et.al.2012] Little research in any setting has examined why. The limited evidence suggests health workers' decisions surrounding whether to use pulse

oximeters may vary depending on children's characteristics such as age, respiratory symptoms, diagnosis, and admission date, and that barriers to pulse oximeter use may include insufficient training, inadequate guidelines, and repair issues.[Ginsburg et.al.2014; Pham et.al.2007; Jones,2010; Berkley et.al.2004; English et.al.2009] I therefore examined this crucial area for my thesis.

1.1.6 The scope of the research for this DPhil thesis

The research for this thesis sets out to determine when and with which groups of children pulse oximeters are used in Kenyan hospitals, how pulse oximeter use impacts treatment provision, and the barriers to pulse oximeter use.

These results can be used to inform the development of effective strategies to overcome barriers and promote pulse oximeter use in Kenyan hospitals, and can inform implementation in other similar settings. Ultimately this could help improve treatment and reduce child mortality rates.

These findings also contribute to the growing research on how and why health technologies do or do not spread within and across health facilities, part of the diffusion of innovation field, a body of work that can help inform effective evidence-based implementation programmes for health technologies.

1.2 The diffusion of innovation literature

1.2.1 What is the diffusion of innovation?

Diffusion of innovation seeks to understand and explain how, when and why an innovation (e.g. a technology, idea, device, behaviour) is or is not taken up by individuals and groups. This is a large field of research that deals with the uptake of technologies in health, agriculture, economics, information technology, and other areas. One of the foundational texts was Everett Rogers' Diffusion of Innovations book, originally published in 1962.[Rogers,1995] Research that followed focused on health technologies, including theoretical discussions, quantitative and qualitative analyses, and the development of models and frameworks, for many health technologies in a range of settings.

It cannot be assumed that a health technology will be widely adopted just because it has been shown to be accurate, reliable, and effective in improving health outcomes. For instance, the WHO's Guidelines for Health Care Equipment Donations states that up to 70% of available medical technology in Sub-Saharan Africa is not used, because of factors such as inadequate training on use, and insufficient technical support.[WHO,2000] I reviewed the diffusion of innovation literature to identify research relevant to the adoption of (post-development) low-technology interventions, such as pulse oximeters. In reviewing this literature I focused on low-technology interventions that share similar characteristics as pulse oximeters (shown in Box 1.2), to identify factors influencing when and why individuals do or do not start using particular innovations, to inform implementation programmes. Given my focus on Kenyan hospitals, I reviewed the literature on diffusion in low-income settings, and due to the paucity of such research, also considered relevant research (e.g. on the uptake of technologies fitting the characteristics in Box 1.2) from other settings.

Box 1.2: characteristics of pulse oximeters, shared by the other low-technology interventions on which I focused in reviewing the diffusion of innovation literature

- Relatively easy to use
- Produce results quickly
- Non-invasive
- Used by doctors, nurses and other HCWs
- Used within hospitals
- Require electricity or batteries
- Do not require lab work for their use
- Do not need consumable accessories (e.g gloves, needles, etc.) to use them
- Relatively low-cost
- Do not require patient consent
- Not paid for by patients

1.2.2 Frameworks and models

There is a wide range of theories, models, and frameworks that describe technology spread and uptake. For example, Davis et.al.(2015) identified 82 theories in the social and behavioural sciences predicting and explaining behavioural change associated with public health interventions. In this section I provide an overview of some of the more influential theories, models and frameworks; I have excluded theories based only on one study.

In his seminal 1962 Diffusion of Innovation book, Rogers "*defined diffusion as the process by which (1) an innovation (2) is communicated through certain channels (3) over time (4) among the members of a social system*". Through discussing examples such as boiling water spread through a Peruvian village, and hybrid corn use in Iowa, he outlined five factors that he identified as most important in determining a technology's spread and adoption: **relative advantage** (over similar technologies)**, compatibility** (within the context), **complexity** (ease-of-use)**, trialability**, and **observability** (whether one can observe others using it before trying it).[Rogers,1995] Berwick(2003)

applied Rogers' innovation diffusion theory to the healthcare context, categorising factors influencing health innovation spread into three clusters: **perceptions of the technology**, **characteristics of those who do or do not use the technology**, and **factors relating to the context where the technology has been implemented**. While Rogers and Berwick classified types of innovation adopters similarly (e.g. early adopters, late majority, etc.), Berwick expanded on Rogers' theory by, for example, considering how contextual factors (e.g. the organisation's characteristics) influence diffusion.[Rogers,1995; Berwick,2003; Lorenzi et.al.2005] Berwick's framework has impacted healthcare and research. For example, Beaton&Freeman(2015) employed Berwick's clusters to evaluate if/how an oral health programme targeting the homeless was adopted by healthcare workers (HCWs); in employing this framework the authors could categorise the adopter types, identify facilitators and barriers influencing diffusion, and thereby develop recommendations for improving programme uptake.

Most subsequent models/theories/frameworks incorporate Rogers' innovation diffusion theory, and, like Berwick, emphasize that context is important for technologies' uptake. 'Context' refers to societal/cultural context (influencing e.g. adopters' perceptions/attitudes, who key decision-makers are), the facility context (influencing e.g. its guidelines, management structure, funding), and sometimes the wider political/economic/environmental context. In each model/theory/framework, enablers and barriers interact to promote or discourage uptake; the level and pattern of spread depend on which factors are present and most influential in that setting.

Greenhalgh et.al.(2004) included 500 empirical and non-empirical studies in their systematic review of technology diffusion in health service organisations, to create a complex model describing innovation diffusion through determinants similar to Berwick's, such as the 'user system' and 'innovation characteristics', and involving additional components such as 'system readiness for

innovation', and 'communication and influence'; the model also makes explicit the complicated interplay between components. With a focus on behaviour, Michie et.al.(2011) developed the Behaviour Change Wheel, based on 19 existing frameworks, to identify constructs explaining behaviour (capability, opportunity, motivation), intervention functions (serving to address issues in these behavioural sources), and policy categories (promoting intervention functions). Also widely used is the Normalisation Process Theory which has three cores: implementation (the process of introducing the behaviour into the organisation), embedding (how it becomes routine), and integration (how it is sustained within the organisation). The theory's components are organised into a complex model of interrelating factors such as cognitive participation, coherence, and reflective monitoring.[May et.al.2009; May&Finch,2009]

There is a trade-off between complex frameworks aiming for comprehensiveness but that can be difficult to apply, especially when constructs have complex and non-intuitive labels. A more straightforward, arguably easier to understand (e.g. using plain language and simple concepts) complex framework is the Theoretical Domains Framework (TDF). This consolidated 33 behavioural theories to develop 14 construct domains representing broad, simple categories such as knowledge, beliefs about consequences, and environmental context and resources. Each domain contains specific constructs.[Atkins et.al.2017]

Some of the above models/theories/frameworks have substantially contributed to public health knowledge through use in an extensive range of studies. For example, in employing the TDF in developing their interview topic guide and framing their results, Murphy et.al.(2014) identified potential theoretical explanations for HCW adherence/non-adherence to guidelines concerning dementia diagnosis and management; Patey et.al.(2012) discuss how their use of the TDF to systematically categorise and conceptualise factors influencing HCW decision-making concerning

ordering of pre-operative tests, facilitated development of recommended interventions to discourage needless testing.

To describe the literature on factors influencing health innovation diffusion, I adapted Berwick's clusters, as these provide a framework to describe factors that might influence diffusion from an extensive range of contexts; in exploring a varied selection of factors from the literature before conducting my research, I could subsequently compare my findings with those identified in the literature to examine similarities and differences.

1. Perceptions of the technology

a) The technology's characteristics

b) Influence of colleagues and guidance

2. Characteristics of those who do or do not use the technology

a) HCWs' preconceptions, beliefs, opinions, attitudes, and knowledge

b) How technology use influences the HCW's role

3. Factors relating to the context where the technology has been implemented

a) Health facility characteristics

b) How the technology fits within the context of the facility

c) How technology implementation was planned and carried out

These are interconnected not standalone factors, discussed in detail below and listed in Table 1.

Table 1.1: Factors that influence health technology dissemination and uptake according to the literature described in Sections 1.2.3-1.2.5; organised in a framework adapted from Berwick,2003

Framework constructs [Berwick,2003]	Factor categories	Specific factors
Perceptions of the technology	The technology's characteristics	Basic characteristics
		Scientific evidence
		Acceptability and compatibility
		Perceived characteristics
	Influence of colleagues and guidance	Colleagues and peers
		Opinion leaders
		International agencies
		Guidelines
		Feedback
Characteristics of those who do or do not use the technology	HCWs' preconceptions, beliefs, opinions, attitudes, and knowledge	Previous experiences
		Attitudes
		Which sources trust and prioritize
	How technology use influences the HCW's role	Role or workflow
		Inadequate time
		Reputation / social status
Factors relating to the context where the technology has been implemented	Health facility characteristics	Facility's structure and characteristics
		Management of the health facility
		Facility's interaction with other facilities
	How the technology fits within the context of the facility	Cost and resource use
		Health facility policies
		Supply
		Storage
		Repairs and spare parts
		Infrastructure
	How technology implementation was planned and carried out	Training
		Monitoring of quality
		Involvement of stakeholders
		Trialability
		Observability
		Communication
		Funding

1.2.3 Perceptions of the technology

Perceptions of technologies are dependent on the technologies' characteristics, and the influence of colleagues and guidance. These perceptions will influence HCWs' choice of whether to use the technology.

a) The technology's characteristics

Clearly HCWs' opinions on technologies' advantages will be affected by the technologies' **basic characteristics**, e.g. how they are operated, how and when they are meant to be used, what problem they address (and its seriousness/magnitude), their comparison to other technologies (their 'relative advantage'), how quickly results are produced. HCWs will vary in which characteristics they most value and prioritize.[Rogers,1995; Denis et.al.2002; de Camargo Jr.et.al.2015; Atun et.al.2009]

If good quality **scientific evidence** demonstrates a technology's effectiveness this can encourage HCWs to assess the technology as beneficial, but such evidence does not necessarily lead to adoption.[WHO,2010; Denis et.al.2002; Palamountain et.al.2012] Thus, nurses in the Maldives identified in questionnaires that the main barrier to evidence-based practice was "*the relevant literature is not compiled in one place*".[Shifaza et.al.2014] An extensive literature base examines barriers to evidence-based practice outside of the innovation diffusion literature, e.g. Leng&Partridge(2017), Haines et.al.(2004).

HCWs' perception of devices as **acceptable and compatible** to their local environment is also important, i.e. are devices appropriate given the cultural and organisational context.[Rogers,1995; Berwick,2003] Some argue that disseminators need to enable local users to adapt new technologies to their context (within reason), thereby improving their relevance for the local context and making local users feel empowered in using them (e.g. a clinic's HCWs could decide whether a clinical reminder to screen for obesity that appears on a computer does so when the nurse evaluates the

patient vs. during the primary care provider's assessment [Damschroder et.al.2009]); adaptation can risk decreasing the effectiveness/accuracy of use.[Rogers,1995; Free,2004; Berwick,2003]

Many agree that, more important than the characteristics of a specific technology, is the HCWs' **perception of these characteristics**, e.g. about accuracy, ease-of-use, reliability and purpose.[Rogers,1995; Pai et.al.2012; Free,2004; Denis et.al.2002; de Camargo Jr.et.al.2015; Zongo et.al.2016] Rogers quotes a Chicago School of Sociology statement highlighting how perceptions are fundamental: "*If men perceive situations as real, they are real in their consequences*".[Rogers,1995] Thus Pai et.al.(2012) argue that HCWs are sometimes reluctant to use Tuberculosis (TB) point-of-care tests because they perceive them to have issues with confidentiality, and in de Camargo et.al.(2015), HCWs' choice of whether to use a new TB diagnostic tool was affected by their perception of the tool's reliability and sensitivity/specificity, and the perceived ease of training in its use; hence, in these studies, whether the tools really did lead to issues with confidentiality, or were objectively reliable, was not as crucial as HCWs' perceptions of these factors.

b) Influence of colleagues and guidance

HCWs' perceptions of technologies are also influenced by interactions with **colleagues and peers** within their social network, and the views of **opinion leaders**, such as those in a position of authority within a healthcare facility and those whose reputation, representativeness and/or trustworthiness is held highly.[Flodgren et.al.2011; Rogers,1995; Robert et.al.2010;29; Atun et.al.2009] Robert et.al.(2010) argue that HCWs' decisions are normally influenced by multiple social interactions, and connections across groups can also be important. Friction between professional groups can slow adoption because of conflicting operating processes, perceptions, and expertise. Free(2004) argues it is important that **international agencies**, e.g. the WHO, publicly support new technologies from

the start of dissemination, particularly if adoption necessitates substantial health system changes; although doing so does not guarantee spread.

Guidelines, at all system levels (health facility, regional, national, international), on how, when and why to use new technologies, can also influence HCW decision-making. To affect HCW behaviour, guidelines must be used, which only occurs if they are widely available, appropriate and clear, are provided by well-respected organisations, and are introduced as part of a multi-approach process targeting individual and organisational factors.[Leng&Partridge,2017; Pai et.al. 2012; Free,2004; Miller&Sikes,2015; Asiimwe et.al.2012]

Evidence shows that HCWs in many settings often do not adhere to healthcare guidelines.[Flodgren et.al.2016; Grimshaw et.al.2004a; Leng&Partridge,2017] For example, in Lugtenberg et.al.(2009), common barriers to Dutch general practitioners using clinical guidelines included HCWs' perception that guidelines were unnecessary (because they were inappropriate or unsupported by sufficient evidence), organisational constraints, and insufficient guideline awareness. Similarly, in Cabana et.al.(1999)'s systematic literature review, frequently identified barriers to clinical guideline uptake included inadequate guideline awareness, unfamiliarity with details of guidelines' recommended practices, and lack of agreement with the guideline or guidelines in general. However, evidence demonstrates that efforts to increase guideline uptake and adherence can be effective: a Health Technology Assessment report found that the majority of the 235 included studies (which used methods such as educational materials/outreach, reminders and feedback to support guideline implementation), improved the quality of health practice, and most studies led to a modest or moderate care improvement.[Grimshaw et.al.2004b] In a Cochrane review of the tools used by guideline producers to encourage guideline uptake, evidence from four randomised trials (again

using educational tools, reminders etc.) indicates that such efforts can increase HCWs' clinical guideline adherence.[Flodgren et.al.2016]

Finally, **feedback**, i.e. comparison of behaviours to guidelines or other HCWs' behaviours, can be effective in changing behaviours. Ivers et.al.(2012)'s Cochrane review of 140 studies on the effect of audit and feedback on clinician behaviour found that feedback often leads to a (small) improvement in care quality, and that feedback is most likely to be effective when HCWs' initial performance is poor, feedback is provided by a colleague or supervisor, it is provided multiple times and through multiple approaches (e.g. written and oral), and it outlines specific goals and ways to achieve these.

1.2.4 Characteristics of those who do or do not use the technology

a) HCWs' preconceptions, beliefs, opinions, attitudes, and knowledge

As Rogers(1995) states: "*Old ideas are the main mental tools that individuals utilize to assess new ideas.(…) The innovation may be "new wine" but it is poured into old bottles (that is, the clients' existing perceptions)*."

The HCW's **previous experiences** with similar technologies affect their views of new ones, and therefore their choices concerning use.[Rogers,1995] For example, insufficient regulation of early malaria rapid diagnostic tests resulted in cheap poor-quality versions being produced, and early experiences with these led HCWs to mistrust such tests.[Miller&Sikes,2015] Similar mistrust led Ugandan HCWs to give anti-malarials to patients with negative test results.[Asiimwe et.al.2012] Furthermore, HCWs' choice to adopt new technologies may be affected by whether previous attempts to introduce other health innovations were successful, and by HCWs' experiences with devices used alongside the new technologies.[Rogers,1995; Bonair et.al.1989]

HCWs' pre-existing **attitudes** may also be influential, e.g. if HCWs are reluctant to change established practices, or do not think the practice targeted by the technology needs to change, vs. if they feel they should always use the latest methods; such attitudes can change over time.[WHO,2010; Malkin,2007; Denis et.al.2002] Psychological factors such as HCWs' tolerance of ambiguity and preferred learning styles can also impact willingness to try new devices.[Greenhalgh et.al.2004]

HCWs' experiences, attitudes, beliefs and opinions will also determine **which sources of evidence they trust and which they prioritize** to help them decide whether to adopt new technologies. Fitzgerald et.al.(2002) used a case study approach to examine how eight medical innovations were adopted in the UK (e.g. a childbirth service delivery system, aspirin use to prevent cardiac issues). They found that the presence/level of scientific evidence for a technology's effectiveness was not associated with its likelihood of successful diffusion. They suggest this may be because HCWs did not trust new evidence over other (perhaps older and outdated) evidence, the HCWs may have valued and trusted aspects of experience over scientific evidence, or may have prioritised other factors such as professional status (which they may have felt could be threatened by adopting new innovations) or financial incentives.[Fitzgerald et.al.2002] Receptivity to particular information sources over others can also vary by innovation type. Rogers describes a study in which it was found that Swedish farmers were more receptive to information from mass media than interpersonal interactions when innovations were not complex but the reverse occurred for complicated innovations.[Rogers,1995]

b) How technology use influences the HCW's role

HCWs may be less likely to use technologies if their use disrupts the **workflow**, alters staff **roles**, or makes HCWs feel they have less decision-making power or ability.[Pai et.al.2012; de Camargo

Jr.et.al.2015; Greco&Eisenberg,1993] Conversely, adoption is more likely if use ameliorates working conditions, e.g. by improving safety.[de Camargo Jr.et.al.2015] HCWs who already have **inadequate time** to carry out their role (e.g. because of staff shortages) may be less likely to adopt new technologies that add to their workload (even technologies that do not require additional time do require an initial time investment to learn how to use and integrate the device within existing workflows), and will more readily adopt technologies that save time.[Zongo et.al.2016; Asiimwe et.al.2012; Rogers,1995] Furthermore, some HCWs may feel their **reputation/social status** will improve if they adopt new technologies, which may prove a powerful incentive for uptake.[Rogers,1995]

1.2.5 Factors relating to the context where the technology has been implemented

a) Health facility characteristics

A technology's implementation is affected by the facility's and health system's **characteristics** and power **structure** and the interactions between the facility and the external environment (e.g. whether the facility is disorganised and fragmented, or well-coordinated with other facilities and the Ministry of Health).[WHO,2010; Malkin,2007; Robert et.al.2010] Adoption likelihood is affected by the country, and whether the facility is urban vs. rural and public vs. private, across which institutional policies, resource availability, and HCW social context may vary.[Pai et.al.2012] Greenhalgh et.al.(2004)'s systematic literature review found that health technologies are more likely to spread at larger health facilities with semi-autonomous and specialised departments, some available resources, and decentralized governing. Other influential factors included the facility's internal communication practices, and management's general view of change and obtaining/using new knowledge. The **management of the health facility** and personnel may impact device spread. A

health system's inefficiency (e.g. concerning recordkeeping, repairs, funding) limited the adoption of a new TB diagnostic technology in Brazil.[Camargo et.al.2015]

A facility's **interaction with other facilities** can also be important. Facilities are more likely to introduce a device to their staff when other similar facilities have done so already, particularly if a threshold of other facilities has been reached and/or the facility is linked with the others by an inter-organisational network or quality improvement collaboration. Competition with other facilities can be influential, as can the degree to which facility staff communicate with other facilities' staff.[Greenhalgh et.al.2004]

b) How the technology fits within the context of the facility

Cost is an important factor in influencing whether facilities adopt new technologies.[Rogers,1995; WHO,2010; Malkin,2007; Free,2004] Adoption costs include the cost of obtaining and transporting the technology, electricity, regular servicing/repairs, replacement supplies, disposal, and cascading changes to related devices/services, including guidelines and staff. These costs affect how administrators and HCWs perceive the potential benefit of a new technology. Small cost increases may be considered worthwhile if there is a large health benefit; however those with budgetary control may not know of these relative health benefits and/or may still focus on absolute financial cost in decisions.[Free,2004] These considerations will need to be re-evaluated over time as a technology's price can decrease dramatically.[Rogers,1995] Pai et.al.(2012) argue that how technologies are financed and how stakeholders financially benefit from them can be as influential for determining spread, if not more so, than the technologies' characteristics. New health technologies are more likely to be adopted by facilities if they reduce resource use (e.g. due to decreased use of more expensive alternatives, reduced over-prescription of medicines).[Denis

et.al.2002; Miller&Sikes,2015] Denis et.al.(2002) suggest that a technology with no significant clinical benefit can still spread if it reduces costs.

Health facility policies can also encourage or discourage equipment use, depending on, for example: which guidelines the facility endorses; and whether the facility's leaders are committed to promoting technology use, the facility's recommendations are coordinated with the Ministry of Health's, their policies were adapted to support the new technology, and/or the facility has instituted barriers or incentives for the technology's use.[Rogers,1995; WHO,2010; Free,2004; Greenhalgh et.al.2004; Bonair et.al.1989; Greco&Eisenberg,1993] Finally, governmental policies can encourage adoption by facilities, particularly if supported with funding.[Greenhalgh et.al.2004]

Without an adequate **supply**, HCWs may limit their use to a subset of the target population, or decide not to use the technology rather than spend time finding a scarce device.[Free,2004; Miller&Sikes,2015; Bonair et.al.1989] One potential cause of inadequate supply is a lack of effective management for timely communication with suppliers. [Miller&Sikes,2015] Device **storage** can limit use if HCWs find it burdensome to retrieve the technology from the storage location. Thus, in Zongo et.al.(2016), HCWs in Burkina Faso were less likely to choose to use malaria rapid diagnostic tests when these were stored somewhere not all could access.

Poor maintenance and **repair** are also factors that might limit use. Engineering World Health conducted a survey in 10 low-/middle-income countries and found that health equipment most commonly broke because of power supply problems (e.g. concerning batteries, power cords), user error (e.g. because of missing/unclear manuals), or insufficient preventative maintenance.[Malkin,2007] Facility staff should have the skills and equipment for efficient and timely repairs (or there should be somewhere to send the technology for this) and for routine servicing; HCWs should also be aware of how to take care of devices to prevent them

breaking.[WHO,2010; Malkin,2007; Palamountain et.al.2012] Malkin(2007)'s survey found that frustration (e.g. because of unavailable spare parts, insufficient repair skills, corruption), often resulted in HCWs not undertaking steps necessary for repairs. This same survey found that **spare parts** might be unavailable if expensive or out of production; and HCWs sometimes prefer to wait for a new device rather than the spare part (particularly if the device was donated). Also, donated technologies sometimes arrive without spare parts.[Malkin,2007] **Infrastructure** is important: insufficient water or electricity may render technologies inoperable, and poor quality roads may prevent device and spare part delivery.[WHO,2010; Malkin,2007]

c) How technology implementation was planned and carried out

The planning and implementation of technology introduction can impact HCWs' knowledge and opinions about the device and thus whether they choose to use it. Thus, **training** can influence HCWs' ability and decisions to use a technology as training can explain the technology's benefits, and how and when to use it and the results. Training must be planned before device introduction; be periodic, not one-off (particularly given high staff turnover in low-income settings, e.g. due to migration); and effective (e.g. training materials/manuals must be clear and written in local languages, if relevant).[WHO,2010; Palamountain et.al.2012; de Camargo Jr.et.al.2015] **Monitoring of the quality** of use is also important because if HCWs use a device incorrectly, it may not function accurately; if HCWs consequently mistrust the results, they may choose not to use the technology again. A monitoring system should be ongoing from the introduction of a technology, and include external evaluation.[WHO,2010; Pai et.al.2012; Palamountain et.al.2012]

Implementation is more likely to be successful if: HCWs (particularly those most likely to be early adopters of the technology), local government officials, and other **stakeholders are involved** in the implementation process; HCWs can **trial** the technology before adopting it, e.g. through free

samples; and **observe** use by others (e.g. through model programmes, particularly in local areas) before taking the risk of trying it themselves.[Rogers,1995; Free,2004; Gladwin et.al.2002] **Communication** about technologies during implementation can influence spread as much, if not more so, as technologies' characteristics.[Pai et.al.2012] It is crucial that communication about the benefits of technology use is easy-to-understand; that HCWs at each hierarchical level learn about these benefits; and that 'mainstream adopters' (those likely to adopt the technology only once others have) learn about the benefits from several trustworthy people, groups, and/or organizations.[Free,2004; Atun et.al.2009] Finally, sustainable **funding** for the technology's supply, running and upkeep must be planned for before implementation.[WHO,2010; Free,2004]

1.2.6 Broader concepts concerning spread

Thus, whether a health technology spreads is dependent both on whether HCWs *choose* to use it and whether they are *able* to. Different factors may influence technology spread across facilities (introduction into the facility) vs. within facilities (uptake by individual HCWs), a distinction that is sometimes overlooked in the studies included in this review of the diffusion of innovation literature. Factors influencing uptake and spread are interrelated and interacting, sometimes emphasizing, contradicting, altering or otherwise affecting each other.[Greenhalgh et.al.2004]

A technology's spread is not dependent on a single event or decision; it is a non-linear process.[WHO,2010; Denis et.al.2002; Robert et.al.2010; Atun et.al.2009] "*Adopting systems are not unified rational actors*" [Denis et.al.2002]: decisions can be made for seemingly illogical reasons, and conflicting decisions can be made by different HCWs/facilities; also, Robert et.al.(2010) argue that uptake decisions are generally made with a short-term view. The initial uptake of a technology can impact on subsequent uptake if structural changes are required.[Denis et.al.2002; Robert et.al.2010]

In some situations, over-adoption occurs, i.e. when technologies are used in situations when experts would argue it should not be used; this can happen if HCWs/facilities do not accurately understand the device, how it is used and its implications, or if HCWs and/or facilities adopt the technology for reputation enhancement rather than for practical reasons.[Rogers,1995] An issue which is often neglected is the distinction and interplay between what Robert et.al.(2010) call 'adoption', i.e. whether technologies are formally introduced into systems, vs. assimilation, i.e. whether technologies are taken up in routine care. Thus, technologies may be adopted by facilities but may not be assimilated if HCWs only use them in certain situations/with specific patients (which ones may differ by HCW) rather than routinely. Berwick(2003) emphasises the difficulty of innovation diffusion in stating that, "*In health care, invention is hard, but dissemination is even harder*".

1.2.7 The use of diffusion of innovation theories and frameworks in this research

After reviewing the main theories used to understand health technology adoption (see Section 1.2.2), I selected the Consolidated Framework for Implementation Research (CFIR) [Damschroder et.al.2009] to assist in planning my research, because of its multi-faceted, expansive and logical nature. The CFIR combines components from 19 previously published theories and models, including those outlined in Greenhalgh's review, to create a more holistic framework demonstrating the factors impacting intervention implementation. This framework's five categories are a) **intervention characteristics** (e.g. effectiveness, ease-of-use), b) **outer setting** (e.g. national guidelines), c) **inner setting** (e.g. health facility policies, funding sources), d) **individuals' characteristics** (e.g. knowledge, perceptions, attitudes, beliefs), e) **process** (e.g. opinion leader engagement in intervention introduction, training). While this framework includes many components, these are organised into a logical and clear structure. Later in the research process (when planning the qualitative data

analyses), I employed the Integrative Model of Behavioural Prediction (IMBP) [Fishbein&Yzer,2003; Fishbein&Ajzen,2010] to assist with analysing the interview findings, because the qualitative data fit well within this framework's constructs. The IMBP takes a different and unusual approach from other frameworks, laying out a logical pathway of necessary steps for each behavioural occurrence. First are factors influencing the HCW's **intention** to perform the behaviour, then factors affecting the HCW's **ability** to perform the behaviour once they have decided to perform it. This approach is relevant to the adoption of pulse oximeters because a range of enabling factors and barriers could affect whether a HCW wants to use a pulse oximeter (their intention) and whether they can (ability). (See Section 4.4).

1.3 This thesis: Pulse Oximetry in Low-Income Settings

1.3.1 Use of and place of thesis research within the diffusion of innovation literature

My research has been informed by and builds upon the diffusion of innovation literature. Whilst it is important to understand the factors that affected the spread of other health technologies and the theorized factors affecting health technology spread in general, in order to promote the adoption of a particular health technology, such as pulse oximeters, it is necessary to understand which factors (whether discussed in the literature or not) are relevant and important for this technology in this setting. This information can then be used to target, remove, or modify factors limiting device spread, and encourage factors enabling/promoting diffusion.

Just as this thesis focuses only on pulse oximeters, a few studies investigate uptake patterns of other specific diagnostic technologies in low-income settings, notably the aforementioned Zongo et.al.(2016) and Asiimwe et.al.(2012) studies which explored the use and opinions of malaria rapid diagnostic tests, through interviewing HCWs and patients in Burkina Faso and Uganda. Similarly, de Camargo Jr. et.al.(2012) interviewed patients, lab technicians, HCWs and managers on the uptake and perceptions of a new TB diagnostic technology in Brazil. However, most health technology diffusion research examines several interventions or takes a theoretical perspective. Examining barriers and enablers of individual technologies is, however, important, so interventions to promote the technology's uptake can effectively target those specific relevant factors. In addition, the previous research has generally investigated the extent of technological uptake at one time-point, rather than over time. In this thesis however, the analysis used a clinical information dataset of admissions to Kenyan hospitals that spanned two and a half years.

Rather than limiting the analysis to testing previously identified factors that potentially influence technology spread, and using a pre-defined model or theory, I examined how and why pulse oximeters have or have not spread across Kenyan hospitals, and how and why individual HCWs use or do not use pulse oximeters in different situations. I then identified an appropriate explanatory framework, and finally compared my findings with those of the diffusion of innovation literature, to determine in which ways my findings are supported by the literature, which of my findings have not been identified elsewhere, and how pulse oximeter use in Kenyan hospitals compares with the diffusion of other health technologies in other low-income settings.

1.3.2 The importance of implementation science

Implementation science, as a field of research, was recognised in the 1980s, and until the late 1990s had a focus on high-income settings.[Lobb&Colditz,2013; Mate et.al.2015] The research aims to determine how to strengthen the implementation of an evidence-based intervention in a 'real-life' context.[Peters et.al.2013; Ridde,2016; Lobb&Colditz,2013; Mate et.al.2015] In its guide to implementation research, the WHO explains the need for more implementation research on health technologies, stating that "*We spend billions on health innovations, but very little on how best to use them. This problem affects everyone, but in particular populations in low- and middle-income countries where the implementation challenges are greatest.[…] Implementation research is of immense value in shining a light on the often bumpy interface between what can be achieved in theory and what happens in practice*".[Peters et.al.2013] The diffusion of innovation literature supports implementation research by providing evidence on factors influencing successful implementation of technologies. Implementation science covers areas such as barriers to uptake, potential solutions, cost-effectiveness, access, sustainability, practicality, appropriateness, and equity.[USAID,2012a]

1.3.3 Pulse oximetry

Pulse oximeters are an effective, low-cost, easy-to-use technology with the potential to improve child health outcomes, and yet, even though international organisations and partnerships including the WHO acknowledge pulse oximetry's importance, often pulse oximeters are not used in low-income settings even when available, and yet little research has examined the barriers to pulse oximeter implementation.

1.3.4 The Kenyan context

Kenya has a population of over 46 million and a life expectancy of 61 for males, 66 for females. In 2014, its total health expenditure was US$78 per capita, which corresponded to 5.7% of GDP (far below the 15% agreed upon in the Abuja Declaration).[WHO,n.d.c; World Bank,n.d.; WHO,2011a] Health system funding is obtained from the government, donors, and patients, with roughly equal proportions coming from each.[KPMG,2013] In 2015, 75,000 children under the age of 5 died, which corresponded to an under-five mortality rate of 51 per 1,000 live births.[WHO,2017c]

In 2014 there were more than 450 county hospitals in Kenya (over 250 of which were government-run).[Kenyan Ministry of Health,2014] In 2013, there was 1 medical doctor and 12 nurses per 10,000 population, compared with the minimum threshold of 23 HCWs set by the WHO.[English,2013; KPMG,2013] Furthermore, HCW distribution is very uneven across the country: one report showed that there was 50-80% understaffing in provincial and rural facilities, and another study showed that the number of nurses can be as low as 0.8 per 10,000 in public sector facilities in some areas.[KPMG,2013; Wakaba et.al.2014] Primary hospitals, referred to as district hospitals, are considered Level 4 (out of 6) / Tier 3 (out of 4) within the health system.[Kenyan Ministry of Health,2014; Kenyan MOH,2015] District hospitals have 50-500 beds. The hospital administrative team is led by a Medical Superintendent who supervises one or two professional administrators. It has been argued that medical and nursing courses do not have adequate management training, which has implications for health technology diffusion, as effective leadership can be crucial for educating about a new technology and encouraging its use.[English,2013] As of 2013 (the year in which the dataset used in this thesis' quantitative analyses began to be collected), there were 47 counties in Kenya. The responsibilities of the county health departments include managing healthcare provision within that county's facilities.[Wakaba et.al.2014]

Guidance documents, developed by and agreed upon by local professionals, on hospital care for children, including pulse oximeter use, are available in Kenya. Thus, the Kenyan Basic Paediatric Protocols, which are guidelines on care for children at admission to Kenyan hospitals, were created in 2005, and revised in 2010, 2013 and 2015, through a series of evaluated processes, systematic reviews, and facilitated panel discussions, that involved local physician and non-physician clinicians, researchers, Kenyan Ministry of Health policymakers, the Kenyan Paediatric Association, and the University of Nairobi.[English et.al.2017b] 10,000 copies of these Protocols were distributed in 2007/2008 and 12,000 in 2010/2011. A training programme on some of the Protocols' guidelines was also conducted with over 1,500 HCWs, and in 2008 this training was introduced into the teaching programme of the country's largest medical school.[English et.al.2014] In 2013, a network of 14 hospitals, called The Clinical Information Network (CIN) was established as part of interventions to improve the quality of Kenyan paediatric care. Through the CIN, data are collected on child admissions to the CIN hospitals, and periodic feedback, including on pulse oximetry, is given to the hospitals on adherence to care guidelines and documentation.[Gachau et.al.2017]

One of the "Dreams" of Kenya Vision 2030 is for "*a Kenya where all Kenyans can afford to go to well-equipped hospitals and get treated by qualified doctors*".[Kenya Vision 2030] The Kenya Health Policy 2012-2030 states that the Policy's goal is "*attaining the highest possible standard of health in a manner responsive to the needs of the population*". The overall objective is to "*attain universal coverage of critical services that positively contribute to the realization of the overall policy goal*"; Policy Objective 1 that supports the overall Policy Objective is to "*Eliminate communicable conditions*", and Policy Objective 4 is to "*Provide essential health care*", one of the targets of which is to "*Ensure provision of quality health care, as defined in the norms and standards and guidelines, and by users*".[Kenyan Ministry of Health,2012]

And yet, despite these policies, and the availability of locally-developed pulse oximeter guidelines and feedback, widespread dissemination and uptake of pulse oximetry has not occurred in Kenya. Previous studies have shown that pulse oximeters are often not available in Kenyan hospitals [English et.al.2014], and I will discuss in Chapter 3 how pulse oximeter use varies substantially across and within Kenyan hospitals over time.

1.3.5 Approach and structure of thesis

To examine pulse oximeter implementation in low-income settings, focusing on Kenyan hospitals as a case study, to understand how best to implement this low-cost, easy-to-use, effective intervention, I conducted this thesis in three parts, using a combination of quantitative and qualitative methods, an approach sometimes termed 'mixed-methods'. I specifically used a planned sequential approach (see Figure 3.2), in which I first conducted a systematic literature review (Chapter 2), which provided a foundation of knowledge to inform the later research components. Then I carried out the quantitative analyses (Chapter 3: methods, Chapter 5: results). The intention was for these quantitative analyses to then inform the data collection and analysis of the qualitative research component (Chapter 4: methods, Chapter 6: results), which served to explain and triangulate the quantitative findings, while addressing wider questions. Finally, I integrated the results (Chapter 7) by examining in which ways the findings from each component supported or contradicted each other, or explored different areas. The three research components examined the following areas:

a) Systematic literature review, to determine how pulse oximeter use with children at admission to hospital impacts health outcomes, specifically mortality, morbidity, and length of stay

b) Quantitative analyses of a dataset of 28,000 children admitted to seven hospitals in Kenya, to determine with which children and in which situations pulse oximeters are being used in these hospitals, and the impact of pulse oximeter use on treatment provision

c) Qualitative analyses of interviews with HCWs and hospital staff in 14 Kenyan hospitals, employing theoretical frameworks, to determine why HCWs choose to use or not use pulse oximeters, why HCWs sometimes cannot use pulse oximeters, and why pulse oximeters were adopted in some health facilities but not in others

I used quantitative and qualitative research methods as the experience of HCWs can provide valuable in-depth qualitative information on practices and opinions, while the quantitative data analyses allowed an examination of the patterns and associations of different factors, in larger populations, over time, with reduced recall and response bias. In using the sequential mixed-methods approach, I used the qualitative data to explain, validate and expand upon the quantitative findings, while examining areas that qualitative research is particularly adept at describing, such as HCWs' opinions and experiences. In consolidating the quantitative and qualitative findings, I gained a more holistic understanding of pulse oximeter use in Kenyan hospitals, and developed a set of recommendations. Throughout the thesis I focused on pulse oximeter use at admission, rather than its use for monitoring purposes.

Studies investigating health technology spread almost always use qualitative methods – generally interviews, sometimes focus groups or surveys. A few studies collect quantitative data through interviews, e.g. quantitatively analysing numerical scores from 5-point scale interview answers.[Lee et.al.2011] An exception is Polage et.al.(2006) who, besides interviewing HCWs to evaluate Ghanaian laboratory testing, also collected quantitative data on e.g. diagnoses and tests run, from medical records and laboratory logs. Therefore, a gap clearly exists in quantitative literature in this

area. As a result, there is little evidence quantifying technology spread and uptake, especially over time, or across facilities or regions, or statistical analyses of factors at the individual or higher level influencing spread. In analysing such data in my thesis, I can more accurately and thoroughly understand diffusion patterns, barriers, and facilitators.

Employing a combination of quantitative and qualitative methods is becoming more common in implementation science and evaluations of health interventions. However, although there are some examples of guidance on conducting 'mixed-methods' research, (e.g. Creswell et.al.(2011), Venkatesh et.al.(2016), Tashakkori&Teddlie(2010), and Padgett(2012)) there is as yet a lack of consensus on the definition of or guidelines for such research, particularly in how to consolidate the results or evaluate the approaches holistically.

A case study approach was selected to examine variability in pulse oximeter use for hospitals contributing data to the CIN dataset. A case study is defined as "*a method of research that engages in the close, detailed examination of a single example or phenomenon, and is an approach commonly used to understand activity and behaviour within a real-life context*."[Rodgers et.al.2016]. Denzin&Lincoln(2005) explain: "*Case researchers seek out both what is common and what is particular about the case*." It has been argued that case studies are most useful when researchers are trying to answer 'why?' and 'how?'; when one cannot control the investigated behaviours; and when the research is examining current, not past, behaviours.[Rodgers et.al.2016] Case studies enable researchers to investigate the context where an innovation is implemented, which helps to provide guidance for implementation of future programmes, and for understanding the generalisability of the findings, and how to adapt the programme to other contexts.[Craig et.al.2006] This case study is both an "*intrinsic case study*", in that I am interested in pulse oximeter use within this particular context, in order to provide information that could be used as part of the

CIN feedback system to improve pulse oximeter use in this context; and an "*instrumental case study*" in that conducting this research on Kenyan hospitals will facilitate our understanding of pulse oximeter use in low-income settings more broadly.[Denzin&Lincoln,2005] Denzin&Lincoln(2005) argue that "*case study can be a disciplined force in setting public policy and in reflecting on human experience. Vicarious experience is an important basis for refining action options and expectations.*(…) *The utility of case research to practitioners and policy makers is in its extension of experience*." Furthermore, in conducting case study research on Kenyan hospitals using data from the CIN, a rare example of a large dataset of 'real-world' data collected in a low-income setting, I am also able to demonstrate how such datasets can be valuable for informing care quality improvement efforts.

There is limited evidence on the patient-level factors that relate to the use of technologies. Studies consider factors affecting whether individuals/groups of HCWs choose to use technologies as though each HCW can be categorized into users or non-users, but in reality, a HCW might make different decisions depending on the patient (e.g. based on age, diagnosis). So, one must not only consider whether a HCW uses a technology, but also with which patients the HCW uses it. I examine this in my thesis.

Ultimately, the findings from this research can be used to help develop effective strategies to encourage appropriate pulse oximeter use, which could help to improve diagnosis and target treatment, and consequently reduce child mortality rates. This could help to achieve the objectives laid out in Kenya Vision 2030 and the Kenya Health Policy 2012-2030, and would assist in global efforts of reducing child mortality in line with Sustainable Development Goal 3.

Chapter 2: Systematic literature review

2.1 Introduction

In newborns, children and adolescents, hypoxemia is associated with increased risk of death, and is a common complication of bronchiolitis, pneumonia, asthma and other serious conditions (e.g. sepsis).[WHO,2014b; Lozano,2001; Djelantik et.al.2003; Orimadegun et.al.2014] Evidence suggests that pulse oximeters identify 20-30% additional hypoxic children compared with using clinical signs alone, e.g. grunting and depressed consciousness, which can be imprecise.[WHO,2014b; Hanning&Alexander-Williams,1995] However, evidence of an association between hypoxemia and mortality is not necessarily evidence that pulse oximetry implementation improves outcomes, particularly taking a broad health system perspective, when healthcare worker (HCW) actions, characteristics of children and health facilities, and additional resources, all interact to impact outcomes.

In the complex world of health systems, pulse oximetry could lead to improved health outcomes and system efficiencies, and reduced resource use, by helping HCWs promptly diagnose children and initiate treatment, and by improving diagnostic accuracy, thereby preventing unnecessary admissions and treatments. Alternatively, pulse oximetry could cause unnecessary admissions, treatment, or referrals, and/or discharge delays, if thresholds for admission, referral or intervention are inappropriate. In high-income countries, guidance for routine screening with pulse oximetry is inconsistent, with some suggesting it is unhelpful.[NICE,2014; Bradley, et.al.2011; NHS,2013; SIGN,2006; Subcommittee on Diagnosis and Management of Bronchiolitis,2006; Healthcare Improvement Scotland, 2014; WHO,2012; Friedman et.al.2014; Ralston et.al.2014] Debate also

remains about optimum hypoxemia definitions, especially at altitude.[Lozano,2001; Brown&Dannenberg,2002; Ingram&Munro,2005; Fouzas et.al.2011; Schult&Canelo-Aybar,2011; Subhi et.al.2009b]

Therefore, for the first stage of my thesis I reviewed the evidence on how pulse oximetry introduction impacts health and service use outcomes. This systematic literature review was published in Archives of Disease in Childhood in 2015 [Enoch et.al.2015]; and an editorial was published as commentary to it.[Moschovis&Hibberd,2016]. This chapter is an adapted version of this literature review. This information could help elucidate the implications of promoting increased pulse oximeter use for children at admission to Kenyan hospitals. Furthermore, examining this evidence, and determining the gaps in the literature, helped with deciding which areas to focus on later in the thesis in the quantitative dataset analyses and the qualitative interviews.

2.2 Methods

2.2.1 Research question

The primary research question that I addressed was:

Do newborns, children and adolescents aged up to 19 years have lower mortality rates, lower morbidity, and shorter length of stay in health facilities where pulse oximeters are used to inform diagnosis and treatment (excluding surgical care) compared to in health facilities where pulse oximeters are not used?

I also addressed the following secondary research question:

What proportion of newborns, children and adolescents are given oxygen therapy where pulse oximeters are used compared to where pulse oximeters are not used?

2.2.2 Eligibility criteria

Studies were included if they recruited newborns, children and/or adolescents aged up to 19, presenting for the first time to a hospital, emergency department (ED), or primary care facility, regardless of setting. Studies assessing pulse oximeters in screening healthy newborns before discharge, or monitoring e.g. during surgery were excluded.

I included studies with at least one intervention group in which a pulse oximeter reading was taken and at least one control group in which pulse oximetry was not used. I included studies reporting mortality, morbidity (illness severity, i.e. pneumonia severity scores, disability at discharge), and length of stay. Descriptive studies were excluded.

2.2.3 Information sources and search process

I systematically searched DARE, Cochrane, Medion, PubMed, Web of Science, Embase, Global Health, CINAHL and the World Health Organization's (WHO's) Global Health Library, with no language restrictions (Search terms - Appendix 2.1). Study references were checked. Websites of non-governmental organisations, health organizations and development organizations were searched for unpublished reports using 'pulse oximeter' and 'pulse oximetry'. Topic experts were contacted for additional materials.

2.2.4 Data collection process

Studies that were not relevant based on title/abstract were excluded. I read the remaining studies' full texts and excluded those not fulfilling the inclusion criteria. All full texts were read by a second person, and if inclusion was uncertain, a third. I extracted data using a tailored Cochrane data collection form; assessed the risk of bias of each study using the Cochrane ACROBAT tool; and evaluated the quality of the evidence for each outcome using GRADE. [EPOC,2014; Sterne et.al.2014; Higgins&Green,2011]

2.2.5 Synthesis of results

I intended to calculate risk ratios, mean differences and confidence intervals, and if possible pool data within subgroups and conduct a meta-analysis. However, due to the small number of studies and the study design/outcome variability I could not. Instead I describe the evidence using a structured approach while drawing insights where possible, a standard strategy in such situations.

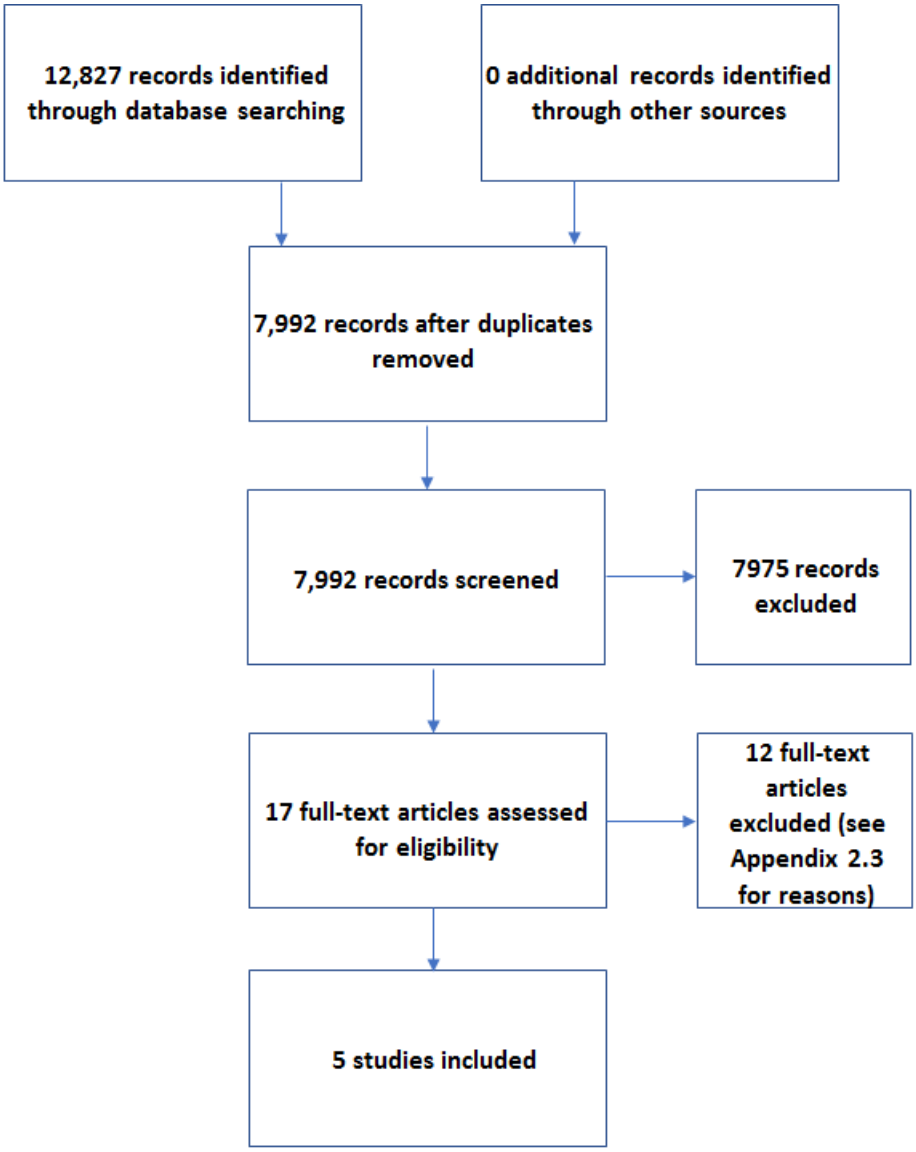
2.3 Results

2.3.1 Search results

I found 7,992 reports after removing duplicates, and screened all titles and abstracts, and the full texts of 17 potentially relevant studies. Five studies[Anderson et.al.1991; Choi&Claudius,2006; Duke et.al.2008; Maneker et.al.1995; Mower et.al.1997], all uncontrolled before-after studies (without independent comparison groups), were included. (Figure 1 has a flow chart showing the study

selection process; and Appendix 2.2 and 2.3 have Characteristics of Included and Excluded Studies tables, respectively).

Figure 2.1: Flow chart showing the study selection process



2.3.2 Risk of bias

The risk of bias rating was based on a four-point scale from low to moderate, serious and critical, as laid out in the Cochrane ACROBAT tool.[Sterne et.al.2014] One of the studies [Choi&Claudius,2006] had a 'moderate' risk of bias; the remaining four were judged to have a 'serious' risk of bias. The areas of greatest concern were bias in selection of participants into the study (Maneker et.al.(1995); Mower et.al.(1997)), bias due to departures from intended interventions (Duke et.al.(2008)), bias in the measurement of outcomes (Anderson et.al.(1991); Maneker et.al.(1995); Mower et.al.(1997)) and bias in the selection of the reported result (Anderson et.al.(1991)). Table 2.1 demonstrates each study's risk of bias.

Table 2.1: Risk of bias ratings for each domain for each study

Study	Bias due to confounding	Bias in selection of participants	Bias in measurement of interventions	Bias due to departures from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of the reported result	Overall
Anderson et.al. 1991	Moderate	Moderate	Low	Low	Low	Serious	Serious	Serious
Choi & Claudius, 2006	Moderate	Low	Low	Moderate	Moderate	Moderate	Low	Moderate
Duke et.al. 2008	Serious	Moderate	Low	Serious	Moderate	Moderate	Moderate	Serious
Maneker et.al. 1995	Moderate	Serious	Low	Low	Low	Serious	Low	Serious
Mower et.al. 1997	Moderate	Serious	Low	Low	Low	Serious	Low	Serious

Risk of bias rating is based on a four-point scale from low to moderate, serious and critical

2.3.3 Intervention effects

Only five eligible studies were included, all uncontrolled before-after studies at high risk of bias; our confidence in the effect estimates is therefore limited with a high level of uncertainty.

Mortality rates

Duke et.al.(2008) reported that mortality rates for children with pneumonia at five Papua New Guinea hospitals decreased by 35% after services were reorganized and pulse oximeters, oxygen concentrators and training were introduced. We cannot determine how much of this mortality improvement was due to pulse oximetry vs. the provision of training, oxygen systems and other changes.

Morbidity

Three studies assessed whether pulse oximeters influence physicians' clinical decision-making. Paediatric physicians assessed children presenting to an ED and decided their treatment before and after obtaining their pulse oximeter results.[Anderson et.al.1991; Maneker et.al.1995; Mower et.al.1997] Studies defined hypoxemia differently and their physicians used different oxygen saturation (SaO2) thresholds to indicate necessary treatment. No independent controls were included, which increased the risk of bias, as did that pulse oximeter results were presented to physicians after their initial evaluations, which could have accentuated the perception of pulse oximetry's value in the clinical process.

No studies directly measured morbidity; however, two examined whether pulse oximeters facilitate morbidity measurement (illness severity scores and diagnosis). Anderson et.al.(1991) asked

physicians to record illness severity assessments, on a 5-point scale, for ill children presenting to the paediatric ward, excluding those with minor orthopaedic/surgical injuries, before and after obtaining pulse oximeter results. When the results were revealed, physicians changed their illness severity assessments for 53% of children; two-thirds of these scores were reduced. Physicians in Mower et.al.(1997) changed the diagnoses in 8% of children with SaO2<95% and 0.7% of children with SaO2≥95% after receiving pulse oximeter results.

Length of stay and influence on admission rates

In Choi&Claudius(2006) the average time spent in a paediatric ED triage when pulse oximeters were used was 17% less than in the same ED a year previously, when pulse oximeters were not used.

Maneker et.al.(1995) reported that 46/69 children (67%) who had low SaO2 (SaO2<92%) had not been clinically expected to have low SaO2, while 23 (33%) had been expected to have low SaO2. After obtaining pulse oximeter results, physicians admitted 13/46 (28%) of children with unexpectedly low SaO2 (who would have been discharged without pulse oximetry) and admitted 1/23 (4%) of children who expectedly had low SaO2. Mower et.al.(1997) found that after receiving pulse oximeter results, physicians admitted five additional children of the 305 who had SaO2<95% (2%) and five additional children of the 1822 who had SaO2≥95% (0.3%).

Secondary research question: treatment and management

Management plans changed for 19% of children in Anderson et.al.(1991); most of these plans became less intense. In Maneker et.al.(1995), management plans changed for 91% of children who unexpectedly had low SaO2 (SaO2<92%); 90% of these were started on oxygen therapy. Management plans also changed for 43% of children who expectedly had low SaO2; 90% of these were started on oxygen. In Mower et.al.(1997), after receiving pulse oximeter results, physicians

ordered new diagnostic tests for 20% of children with SaO2<95% and for 0.5% of children with SaO2≥95%; they ordered new treatments for 11% of children with SaO2<95% and for 1% of children with SaO2≥95%.

Table 2.2 shows results along with GRADE assessments for each outcome; Appendix 2.4 has detailed results.

Table 2.2: Summary of findings

Pulse oximeters vs. no pulse oximeters to inform diagnosis and treatment (excluding operative surgical care)					
Population: newborns, children and adolescents aged up to 19 years Intervention: pulse oximeter readings Control: populations with no pulse oximeter readings Outcomes: mortality rates, morbidity, length of hospital stay					
Outcomes	**Overall outcome difference between control and intervention group**	**Number of participants by outcome (studies)**	**Relative effect (with 95% CI)**	**Absolute effect (with 95% CI)**	**Quality of the evidence - GRADE**
Mortality rates	The introduction of pulse oximeters alone may lead to a reduction in mortality rates.	11,291 (1 – Duke et.al. 2008)	RR: 0.648 (0.533, 0.788)	Reduction of 1.75% (1.101, 2.398) or 17 fewer deaths per 1000 patients	Very low[i]
Morbidity	-When pulse oximeter results are obtained in the ED, the assessed degree of illness and the diagnosis for children may be different than if pulse oximeter results are not obtained. This is especially the case for children who do not have a diagnosis of 'well', 'minor orthopaedic injuries' or 'minor surgical injuries', and/or is more likely in	2564 (2 – Anderson et.al. 1991; Mower et.al. 1997)	n/a	n/a	Very low[i]

	children who have low SaO2 values.				
Length of hospital stay	The introduction of pulse oximetry into triage may decrease the average time children spend in triage and may increase the proportion of hypoxic children who are admitted.	622 (3 – Choi & Claudius, 2006; Maneker et.al. 1995; Mower et.al. 1997)	Time spent in triage: Mean difference: 50 minutes (5.405, 94.595) Proportion of hypoxic children admitted: n/a	Time spent in triage: 17 fewer minutes spent in triage per 100 minutes Proportion of hypoxic children admitted: n/a	Very low[i]
Secondary research question: treatment and management	When pulse oximeter results are obtained in the ED, the management plans for children may be different than if pulse oximeter results are not obtained. This is especially the case for children who do not have a diagnosis of 'well', 'minor orthopaedic injuries' or 'minor surgical injuries', and/or is more likely in children who have low SaO2 values, particularly if these are unexpectedly low.	2633 (3 – Anderson et.al. 1991; Maneker et.al. 1995; Mower et.al. 1997)	n/a	n/a	Very Low[i]

[i] These non-controlled before-after studies were downgraded to Very Low due to high risk of bias, indirectness, and imprecision (see Appendix 2.4 for more details)

2.4 Discussion

Pulse oximeters are routinely used in high-income countries, but are implemented without consistent guidelines of when/how to use them and little research on how their routine use impacts health outcomes or resources. New programmes encouraging pulse oximeter use in low-income countries should address these inadequacies in the evidence-base and promote evidence-based decision-making.

Only five studies, all before-after studies at high risk of bias, were identified. Potential dissimilarities in patient/location characteristics existed between time periods in two studies (Choi&Claudius(2006); Duke et.al.(2008)); there were no independent controls in three (Anderson et.al.(1991); Maneker et.al.(1995); Mower et.al.(1997)), and in these, physicians were perhaps more inclined to respond to pulse oximetry because results were given after, not during, initial evaluations (unlike outside study settings). In the study providing mortality data (Duke et.al.(2008)), oxygen concentrators, training and other improvements were introduced with pulse oximeters; while this study points to important effects of improving oxygen therapy systems, from identification to management, it provides only indirect information on possible effects of wide-scale pulse oximetry adoption, e.g. primary care facilities for guiding referral. Other challenges in generalising the findings are that the studies were conducted in the United States and Papua New Guinea and none were conducted in primary care facilities. Although the data are drawn from United States studies and those conducted over 15 years ago, available results have some value as they suggest how pulse oximeter introduction impacts physicians' decision-making, the key mechanism by which pulse oximetry influences practice.

Study design limitations reduce our confidence in the included studies' effect estimates. However, there is some evidence to indicate that pulse oximetry may lead to improved health outcomes, with lower mortality rates (when combined with improved/adequate oxygen administration) and reduced time in ED triage; pulse oximetry may change physicians' decisions

regarding illness severity, and increase hospital admissions related to previously unrecognized hypoxemia (note: hypoxemia definitions varied from <92-95%). Routine pulse oximetry may also influence diagnostic tests and treatments used. Mower et.al.(1997) argue that physicians generally accurately judged SaO2 clinically when very high/low, but made more management changes when moderately low.

It is unclear from the literature how pulse oximetry impacts resource utilization, even though pulse oximetry campaigns focus on low-income settings, where cost-effectiveness is crucial. In Maneker et.al.(1995) and Mower et.al.(1997) pulse oximetry increased resource use through increased admissions and oxygen therapy for children with otherwise undetected hypoxemia. Pulse oximetry led to reduced resource utilization in two studies: in Anderson et.al.(1991) two-thirds of children whose illness severity scores changed were then considered less severely ill, and two-thirds of children whose management plans changed were then managed less aggressively; in Choi&Claudius(2006) pulse oximetry led to reduced triage time.

Pulse oximetry could facilitate quicker diagnosis, so effective treatment starts earlier and recovery likelihood increases, reducing future resource use. Oximetry can reduce resource waste by indicating when to end treatment, and by decreasing false-positives. However, in Schroeder et.al.(2004), hospital stays were on average 1.6 days longer because of pulse oximetry as 26% of children met discharge criteria except needing oxygen according to pulse oximeters. If additional treatment was unnecessary (e.g. inappropriate thresholds were used), then resources were wasted (as the authors assumed). However, if pulse oximetry enabled detection of hypoxic children who would not otherwise obtain treatment, then the additional resources were justified.

Although not discussed here, pulse oximetry also has important resource implications in outpatient facilities, where hypoxemia prevalence in children, while lower than in hospitals, is still considerable (e.g. 4-12%)[Lozano,2001], and where pulse oximetry could facilitate timely

recognition of necessary care or referral to hospital. Appendix 2.5 contains figures illustrating the range of effects of introducing pulse oximetry.

Randomly assigning health facilities to pulse oximeter introduction (with training) or no pulse oximetry could provide robust data on resource use (admissions, diagnostic tools, treatments, referrals, length of stay), health outcomes (mortality, morbidity, re-presentations), and which thresholds, if any, would be most effective for treatment initiation, if studies were sufficiently large. Such pragmatic studies could be done alongside implementation programmes and could elucidate whether pulse oximetry impacts resource use and health outcomes within cost-effectiveness analyses.

If evidence suggests pulse oximetry increases resource utilization then HCWs, facility managers and public health practitioners would need to weigh cost-benefit trade-offs between using scarce resources on pulse oximetry or on other interventions. Context-specific formal cost-effectiveness analyses could be performed to help address these issues but these are rarely done when technologies are introduced into low-income countries' health systems. Such research should be independent and transparent evaluations feeding into wider, evidence-based and inclusive processes for decision-making on resource allocation within health systems.

More research is also needed on the best ways to use pulse oximeters, particularly concerning SaO2 thresholds. In high-income settings, disease management guidelines rarely recommend SaO2 thresholds for diagnosing, evaluating or monitoring children.[NICE,2014; Bradley et.al.2011] When specific SaO2 thresholds are recommended, they differ across organizations, even though the WHO's 2012 Recommendations for Management of Common Childhood Conditions provide clear guidance that oxygen be administered if SaO2<90% (for children at ≤2500m).[NHS,2013; SIGN,2006; Subcommittee on Diagnosis and Management of Bronchiolitis, 2006; Healthcare Improvement Scotland, 2014; WHO,2012] Conversely, the Canadian Paediatric Society warns "*it is important to recognize that setting arbitrary thresholds for oxygen therapy*

will influence admission rates".[Friedman et.al.2014] Setting thresholds is complicated because pulse oximeter results may not be considered in isolation from clinical findings, SaO2 can naturally fluctuate over a day, and studies show that 'healthy' SaO2 differs by age and altitude.[Fouzas et.al.2011; Schult&Canelo-Aybar,2011; Subhi et.al.2009b; Vargas et.al.2008; Kakalia&Khan,2017] A few studies have investigated whether outcomes are comparable when thresholds higher than the WHO's <90% are used: Cunningham et.al.(2015) found cough resolution time in children with bronchiolitis was equivalent when a <94% or <90% threshold was used for oxygen therapy; while Lazzerini et.al.(2015) found that hypoxemia predicted elevated mortality risk in children with ALRI when a <92% or <90% hypoxemia threshold was used; and Hooli et.al.(2016) found that an SpO2[1] of 90-92% in children with pneumonia in Malawi was associated with elevated mortality risk. It is therefore perhaps unexpected that no studies have examined health system consequences of implementing the WHO guidance of using SaO2<90% thresholds.

In absence of clear guidelines, opinion differs on which thresholds should indicate hypoxemia and prompt admission, referral, oxygen therapy, or other treatments. When emergency physicians were surveyed, there was considerable variability in the lowest SaO2 for which they would discharge a 2-year-old with pneumonia and a 10-month-old with bronchiolitis.[Brown&Dannenberg,2002] Maneker et.al.(1995) and Mower et.al.(1997) defined low SaO2 as ≤92% and <95% respectively, thus reducing results comparability.

Threshold choice can substantially impact health system outcomes; thus in Schuh et.al.(2014)'s randomized clinical trial of infants (excluded from this review because all children received pulse oximeter readings), admission rates were sensitive to small saturation differences: 41% of

[1] Pulse oximeter results are SpO2 values, which are, in most cases, very similar to SaO2 values [Chan et.al.2013]. Some studies therefore refer to pulse oximeters' output as SaO2 values while others use the term SpO2. In this systematic review, I have used the terms as the study authors used them; therefore, the terms are essentially used interchangeably. Examples of situations in which pulse oximeters' SpO2 readings may not accurately estimate SaO2 values are discussed in Section 6.3.3.

children in the control group were admitted within 72 hours vs. 25% of children whose displayed SaO2s were artificially increased by 3%. Similarly, Mallory et.al.(2003) found that twice as many physicians who were sent vignettes describing cases, said they would admit a child with an SpO2 value of 92% than would admit a child with a value of 94%.

Finally, when a basic follow-up search was conducted in November 2017, the only additional study found was one conducted in Laos [Gray et.al.2017] where pulse oximeters, improved oxygen systems and associated training were introduced into 20 hospitals (10 were controls where no oxygen systems or training were introduced, but pulse oximeters were introduced into all hospitals). Following the intervention, in both the intervention and control hospitals, there was an equivalent reduction in the proportion of children with pneumonia who were discharged while still ill (while some of this may have been due to the pulse oximeter introduction, the researchers note that it was largely due to a reduction in parents discharging their children against medical advice, rather than a change in HCWs' decisions). Mortality rates reduced from 2.7% (19/712) to 0.8% (6/691) in intervention hospitals, but there was no change in control hospitals; we cannot determine what proportion of this change was due to the introduction of pulse oximeter training in the intervention hospitals vs. the improved oxygen systems. Oxygen saturation documentation increased in the control and intervention hospitals following the intervention, and there was a larger increase in the intervention hospitals. The greater increase in intervention hospitals could be because of the pulse oximeter training in these hospitals (so HCWs were more aware of how and why to use pulse oximeters), and/or because of the improved oxygen systems in these hospitals (e.g. because HCWs had more of an incentive to use the pulse oximeters if they knew they could give oxygen if necessary). For this review's purposes, this study was limited by being a before/after study, and we cannot disentangle the concurrent influence of the improved oxygen systems. The study does not therefore provide substantial new evidence for this review.

2.5 Conclusions

This systematic literature review suggests that pulse oximeter use with children at admission to hospital can reduce mortality rates (when combined with improved oxygen administration) and time spent in triage, increase admissions of children with hypoxemia, and can change physicians' perceptions of illness severity and their treatment decisions. However, the review also highlights that there is little evidence, from any region or setting, on the impact or optimal use of pulse oximeters when children present to a health facility. This review's findings helped to inform the planning of the quantitative and qualitative components of this thesis, by highlighting the need to further explore particular areas, for example, the impact of pulse oximeter use on treatment decisions, and the use of oxygen saturation thresholds for deciding whether to give oxygen.

Chapter 3: Methods and analysis plan for quantitative analyses

3.1 Introduction

Pulse oximeters are often not available in low-income settings, and if they are available, they are frequently not used [WHO,2008; English et.al.2014; Walker, et.al.2009; Desalu et.al.2011; McCollum et.al.2013; Ginsburg et.al.2014; Ginsburg et.al.2012], and yet little research has examined why this is the case. I used a combination of quantitative and qualitative methods to investigate pulse oximeter use in Kenyan hospitals, a setting where pulse oximetry varies widely within and between hospitals over time (See Section 3.2.3). The quantitative component of this research (methods are presented in this chapter and the results in Chapter 5) consisted of analysing data from 28,000 children admitted to seven Kenyan hospitals from September 2013-February 2016, to better understand in which situations pulse oximeters are used, and the impact of their use on treatment. The qualitative research component (discussed in Chapters 4 (methods) and 6 (results)) consisted of interviews with 30 staff from 14 Kenyan hospitals. The interview findings served to verify and explain the dataset analyses, while exploring further areas, particularly concerning barriers to pulse oximeter use (See Section 3.3.5 for more details). In consolidating the dataset analyses and interview findings I developed a list of recommendations (see Section 7.4) for the hospitals that contributed data, and hospitals in similar settings, of changes which could lead to increased pulse oximeter use, and thereby more efficient diagnosis and treatment, potentially resulting in reduced child mortality.

In this chapter, I will first discuss the background for the dataset analyses, then describe the aims, Research Questions, data setting and population, followed by an explanation of the methods and analysis processes I carried out.

3.2 Background

3.2.1 Low pulse oximeter use in low-income settings

The literature indicates that pulse oximeters are often not used, or even available, in low-income settings.[WHO,2008; English et.al.2014; Walker et.al.2009] Thus only 38% of Nigerian tertiary hospitals and three of 22 Kenyan hospitals providing physician internship training had pulse oximeters in 2011 and 2012 respectively.[English et.al.2014; Desalu et.al.2011] McCollum et.al.(2013)'s study in five Malawian hospitals in 2011 showed that only 13% of children obtained a pulse oximeter reading at admission to one of the hospitals while no readings were obtained in four hospitals. Of hospital clinicians across Cambodia surveyed in Ginsburg et.al.(2014)'s study, roughly half said they either never use pulse oximeters to help diagnose and manage childhood pneumonia or do so only "a little bit of the time". In a survey of 97 clinicians from 19 countries in Africa, Asia and South America, at least one pulse oximeter was available at 71% of health facilities but only 59% of clinicians said they have access to a pulse oximeter most or all of the time; moreover only 18% said they use pulse oximeters for help in diagnosing childhood pneumonia most or all of the time, while 44% said they had never done so.[Ginsburg et.al.2012] It is important to obtain a better understanding of why pulse oximeters are not used, particularly when they are available, and also when/with which children they are used. Of course even if pulse oximeters are available and used, children cannot obtain the benefits if there is not also a reliable oxygen supply, which there often is not in low-income settings.[Moschovis&Hibberd,2016; Graham et.al.2017; Duke et.al.2008]

3.2.2 Summary of the evidence indicating the groups of children with whom pulse oximeters are most likely to be used

The evidence indicates that pulse oximeter use may vary depending on children's characteristics such as age, respiratory symptoms, diagnosis, and admission date, as shown in Box 3.1.

Box 3.1: Evidence of groups of children with whom pulse oximeters are most likely to be used

- **Age**: A national study on pneumonia care in American emergency departments found that physicians' pulse oximeter use differed by patients' age.[Pham et.al.2007]
- **Respiratory symptoms**: Only 45% and 10% of British intensive care unit nurses in Jones(2010)'s study thought that pulse oximetry was indicated in patients with respiratory distress and respiratory failure, respectively, indicating that respiratory symptoms can impact pulse oximetry decisions.
- **Diagnosis**: Most of the Cambodian clinicians in Ginsburg et.al.(2014)'s study thought that pulse oximeters are more useful for general care than for managing pneumonia care.
- **Admission date**: Berkeley et.al.(2004) found that admission dates can be influential: the mortality rate of children with weekend admission to a district Kenyan hospital was 6% (171/2754) compared with 5% (487/10139) for those admitted on weekdays (OR: 1.31; 95% CI: 1.10-1.57); they argued that delays in hypoxemia identification and treatment may have considerably driven this disparity. Kenyan hospital care also differed on weekends vs. weekdays in English et.al.(2009)'s study: children under five presenting on weekdays were treated in maternal and child health clinics, but were treated at general outpatient or casualty departments if presenting on weekends or evenings.

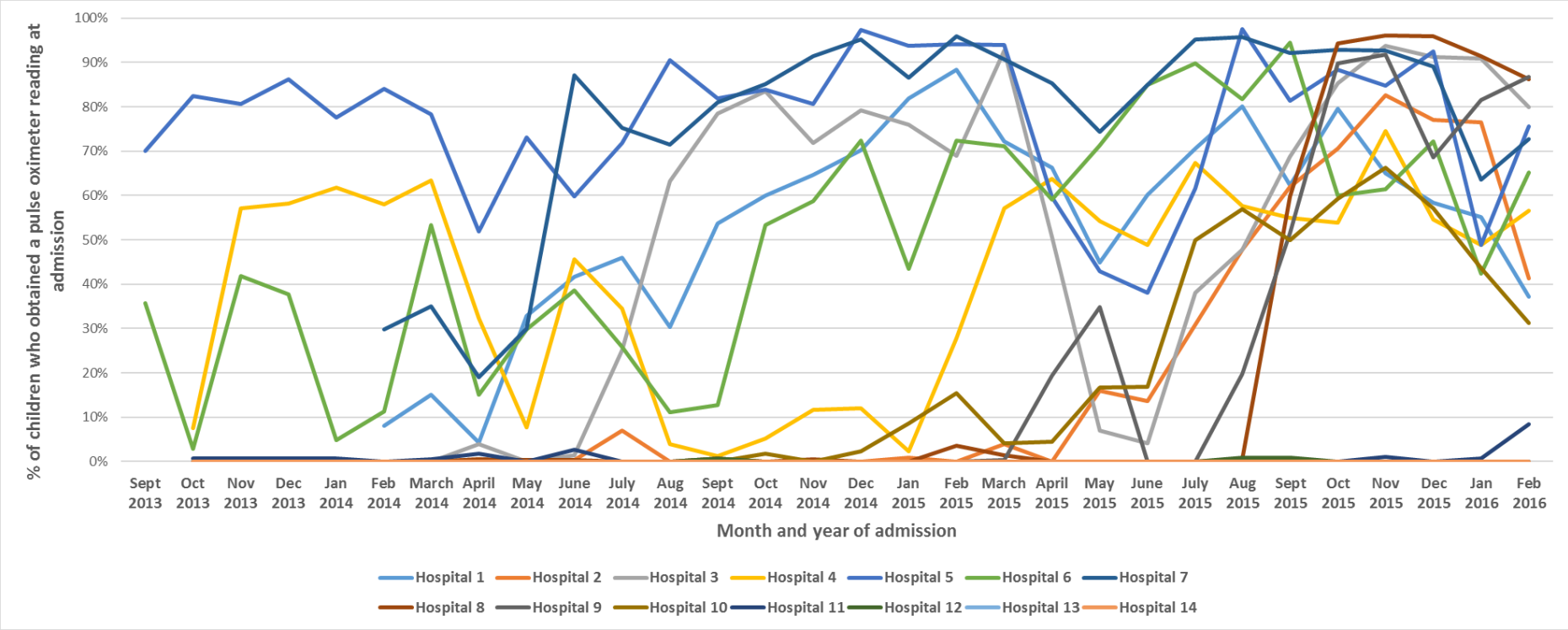
3.2.3 Pulse oximeter use across and within Kenyan hospitals over time

Kenyan hospitals present a good case study on pulse oximeter use in low-income settings given the variability in pulse oximeter use within and across hospitals over time. A network of 14 Kenyan hospitals, termed The Clinical Information Network (CIN), was set up in 2013 as part of a

programme to improve paediatric care quality.[Tuti et.al.2016b] Through the CIN collaboration, data are collected on child admissions to the CIN hospitals (Section 3.3.4 contains more details). It is this 'real-world' [Sherman et.al.2016] data that I used for my quantitative analyses. Pulse oximeter use varies substantially across these CIN hospitals. From September 2013-February 2016, 13 of the 14 CIN hospitals had at least one pulse oximeter, although pulse oximeters were not used at two of the hospitals where they were available, and pulse oximeters were used with 7-75% of children at the remaining hospitals (see Appendix 5.2).

Pulse oximeter use also varied considerably within hospitals over time, as shown in Figure 3.1. (Appendix 3.1 contains individual hospital plots). We can see from this that, while pulse oximeter use increased over time, this was not a steady increase. At every hospital where pulse oximeters were used, the level of use varied over the time period, sometimes quite dramatically (e.g. 93% of children obtained a pulse oximeter reading at Hospital 3 in March 2015; by May 2015, only 7% did); i.e. gains were often followed by falls. Furthermore, healthcare workers (HCWs) at four hospitals almost never used pulse oximeters during this time, while at three other hospitals, pulse oximeter uptake began in the last 6-12 months of the study period.

Figure 3.1: Pulse oximeter use over time by hospital



Note: hospitals entered in to the CIN at different months (all had entered by February 2014), so lines in Figure 3.1 begin at different dates; see Appendix 3.1 for individual figures for each hospital; only data for Hospitals 1-7 were included in the descriptive and regression analyses – see Section 3.5.2 for reasoning

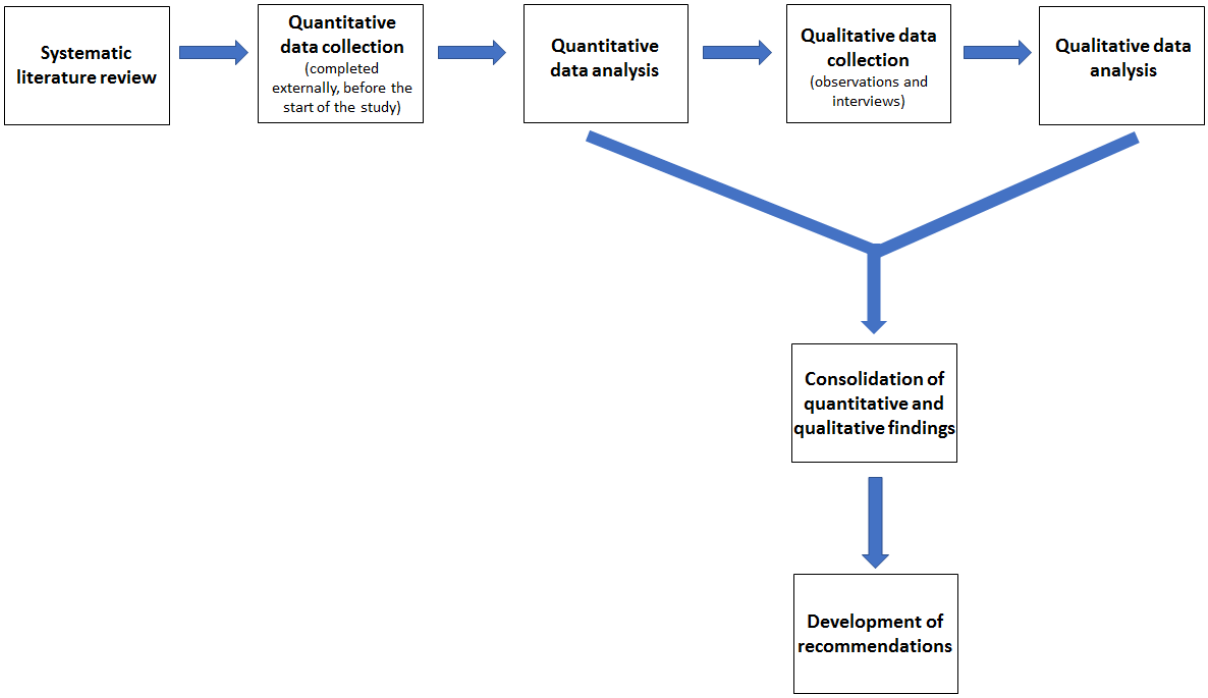
3.3 Objectives and study design

3.3.1 Mixed-methods approach

I used a sequential mixed-methods approach (see Figure 3.2) to examine pulse oximeter use in Kenyan hospitals. I first carried out a systematic literature review to ground myself in the literature on the impact of pulse oximeter use on health outcomes (Chapter 2); then conducted quantitative analyses of the CIN data to understand with which children pulse oximeters are used and the impact of pulse oximeter use on treatment provision (Chapters 3 and 5); the intention was also for these quantitative analyses to then inform the data collection and analysis of the qualitative research component (Chapters 4 and 6), which served to explain and triangulate the quantitative findings, while addressing wider questions on barriers to pulse oximeter use; the integration of the quantitative and qualitative findings (Chapter 7) then served to build an in-depth, multi-faceted understanding of pulse oximeter implementation in this setting, and to facilitate the development of effective recommendations (See Section 7.4). For purposes of clarity, I describe each research stage individually.

The sequential mixed-methods approach employed in this thesis is illustrated in Figure 3.2.

Figure 3.2: Sequential mixed-methods approach used in this research



Factors enabling, promoting or discouraging pulse oximeter use may be found at different levels of the health system hierarchy, e.g. there may be factors influencing the interaction between the HCW and patient (such as HCW beliefs and knowledge); at the departmental level (e.g. departmental policies, influence of consultants); at the hospital level (e.g. hospital policies, hospital procurement systems and financing); and at the county, national and international levels (e.g. guidelines, policies, financing). See Appendix 3.2 for a diagram of these levels. The dataset analyses explored the factors influencing the interaction at the first of these levels, the HCW-patient interaction, while the qualitative interviews examined factors operating at all health system hierarchy levels.

3.3.2 Aims of the quantitative dataset analyses

The Kenyan hospitals that contribute data to the CIN presented a rare opportunity to study and understand the use of pulse oximeters in a routine low-income setting. In particular, they allow exploration of the variability in pulse oximeter use within and across hospitals over time, and

how, if at all, pulse oximeter results influence HCWs' treatment decisions when pulse oximeters are used. This information indicates whether national and international guidelines on pulse oximeter use [WHO,2014b; WHO,2013; Kenyan Ministry of Health,2016] are being followed.

3.3.3 Research Questions

1) Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

2) Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?

3) Are pulse oximeter readings below 90% associated with the prescription of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?

Note: the 90% threshold was chosen because the World Health Organization (WHO) and the Kenyan Basic Paediatric Protocols, which are the national guidelines for hospital care in children, both recommend that if a child's oxygen saturation is below 90%, oxygen should be given. [WHO,2013; Kenyan MoH,2016]

Secondary question: Are the results for Research Questions 1-3 different for children who have vs. do not have pneumonia?

3.3.4 Clinical Information Network Dataset

The clinical data that I used were collected as part of the CIN. This network of 14 Kenyan hospitals was set up in 2013 as part of a collaboration between the Kenyan Ministry of Health, the Kenyan Paediatric Association, and the Kenya Medical Research Institute (KEMRI) Kenya

Wellcome Trust Research Programme (KWTRP), which itself is a collaboration between the Kenyan Ministry of Health, the Wellcome Trust and the University of Oxford.

As part of this network, trained data clerks collect data on up to 350 variables (demographics, symptoms, diagnoses, treatments and outcomes) from the paper medical records of children admitted to the 14 CIN hospitals. These data are collected when the child is discharged and are entered into an electronic system and anonymised. A procedure of electronic and manual checks are in place to check data quality. Feedback is given on documentation completeness and adherence to care recommendations (including on pulse oximetry) through audit reports (created through analytic scripts run on the data, and displaying performance for particular indicators for the current reporting period vs. previous period vs. the average for all CIN hospitals) sent to hospitals (specifically to the Medical Superintendents, paediatricians, nursing officers in charge, and senior data clerks) every 2-3 months, combined reports provided to the Kenyan Ministry of Health, yearly face-to-face meetings with HCWs and data recorders, and regular telephone and email discussions with paediatricians. The feedback is most directly targeted to paediatricians (mid-level managers), with the intention for them to share this information with their ward team.[Gachau et.al.2017; Tuti et.al.2016a]

3.3.5 Justification of the methods

The limited evidence to date on when and with whom pulse oximeters are used in low-income settings has largely been from cross-sectional surveys and interview studies. These methods can provide in-depth and multi-faceted understanding of contextual factors, and are effective for obtaining information on HCWs' perspectives, opinions, and experiences. However, they are not objective measures of behaviour; are examples from often a single context, not a representative sample that can be generalised to the population; are not an effective means by which to

measure progression of changes over time; and the findings can only be described, with limited ability to critically analyse associations and relative importance or occurrence of factors influencing pulse oximetry. Therefore, using only these methods provides a partial understanding of pulse oximeter use.

The CIN dataset is a rare example of a large clinical dataset of relatively good quality medical record data collected over time from a low-income setting. Large scale routine datasets like this provide an opportunity to obtain a more detailed understanding of the breadth and frequency of behaviours across a HCW population (which is important for determining which behaviours to target in pulse oximeter promotion programmes); examine variations over time; and identify patterns of use that might apply to similar settings, e.g. other low-income settings where resources are limited and there are gaps in equipment availability and use. Another example is a dataset of mortality and morbidity data on nearly 100,000 admissions to 16 hospitals in Papua New Guinea over six years, which helped inform the country's national health plans and associated health improvement programmes; however, this dataset had limited patient level clinical data.[Duke et.al.2016] As far as I am aware, there are no studies on pulse oximeter use in a low-income setting (or evaluation of uptake of other diagnostic tools in such settings) that utilise this type of data.

The hospitals that contribute data to the CIN are a sample of hospitals in Kenya; the criteria used to select hospitals for the CIN are described in Ayieko et.al.(2016), and included that each is located in a different county (with two exceptions), and is a public hospital (but not a tertiary-level facility) with at least 1,000 yearly child admissions. Using data from these hospitals provided an opportunity to investigate and compare pulse oximeter practices in a range of settings across a low-income country. Furthermore, the Kenyan Ministry of Health has developed a set of national guidelines on hospital care for children [Irimu et.al.2014] and continues to support the use of these guidelines [English et.al.2014]; this research can also serve

as an audit of HCWs' adherence to these guidelines. Moreover, the CIN was established to improve the quality of hospital care for children through e.g. giving feedback on data collection and care quality to the hospitals and HCWs; this research provides insight into how successful these efforts have been in increasing appropriate pulse oximeter use; and aligns with the CIN's aim by providing recommendations to help develop evidence-based interventions to increase appropriate pulse oximeter use.

This research is crucial for facilitating effective pulse oximeter promotion programme development, and for demonstrating how clinical data from a low-income setting can be used to improve health outcomes, as programme planners could use its findings to understand which HCW behaviours and perceptions to target. These pulse oximeter promotion programmes can in turn improve the prompt diagnosis and treatment of children, potentially leading to reduced child mortality.

3.4 Conceptual diagrams to frame thinking surrounding the clinical process and support the quantitative modelling

I created three conceptual diagrams (Figures 3.3a-c) to help frame the decisions, actions, and pathways involved in the clinical process of child admissions: a general framework, a framework with all variables included in the analyses, and a framework for children admitted specifically with pneumonia.

These diagrams demonstrate the sequence of the clinical processes and the relationships between the variables for which we have data. Developing these diagrams helped to formulate my approach to investigating the Research Questions, for instance by helping me to decide which variables to include in the regressions. Also, in using these diagrams before conducting the analyses to describe the relationships between the variables, I ensured that the analyses

were not misled by potentially spurious associations that may otherwise have seemed in need of explanation after conducting exploratory statistical analyses.

I created the general framework for an overview of the process; the framework with all variables included in the analyses to conceptualise and consolidate the components I was planning to analyse; and the framework for children admitted with pneumonia to reflect on child characteristics, HCW considerations, and process steps specific to children with pneumonia, to inform the analyses of the subset of children with pneumonia.

Figure 3.3a: Conceptual diagram of general clinical process through child admission and an iterative process of review and revision as appropriate. Primary outcomes of interest are pulse oximeter use and oxygen use (Shaded boxes occur on first day of admission; components in bold are included in these analyses; page i has list of abbreviations)

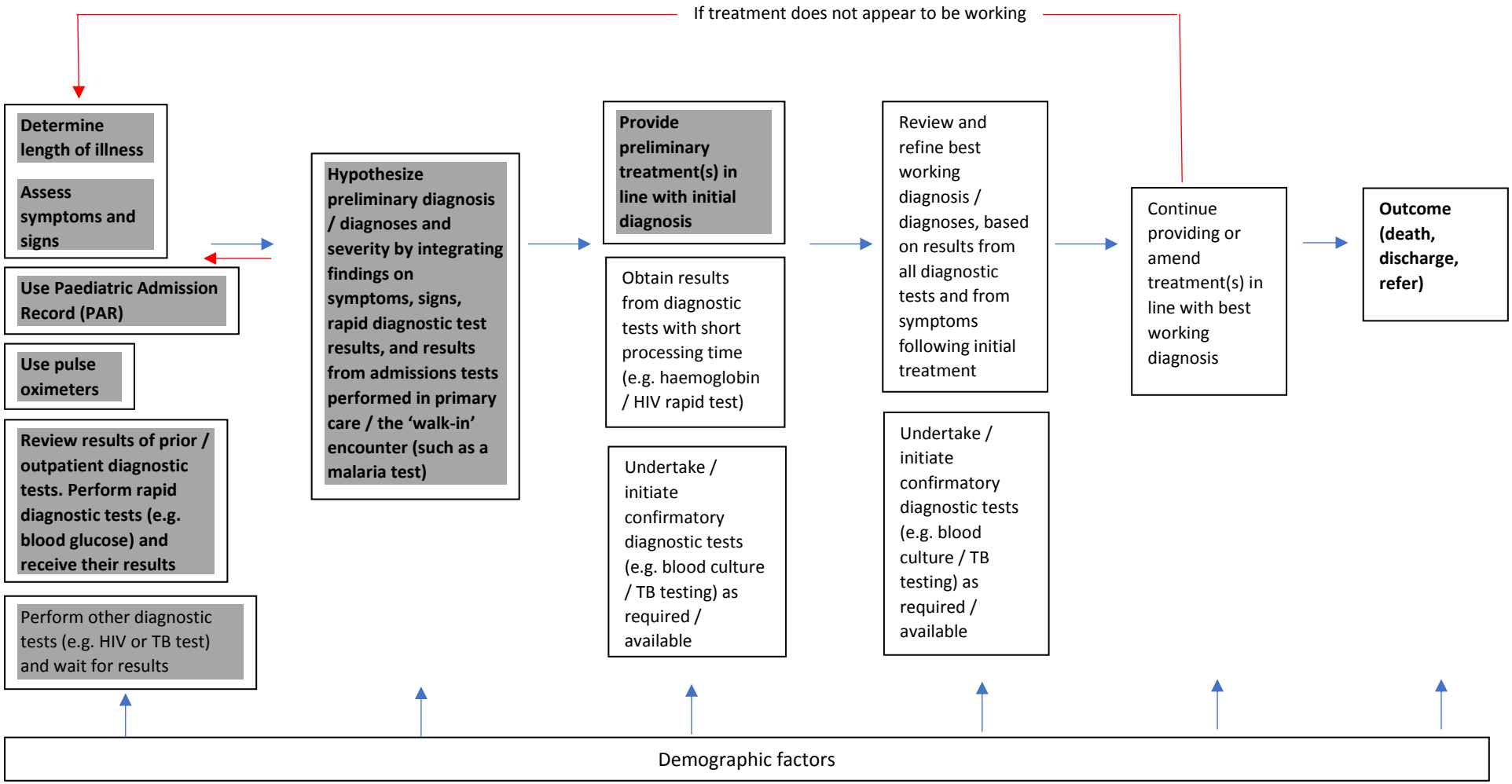


Figure 3.3b: Conceptual diagram of clinical process in all admitted children with any diagnosis, with the most relevant variables (from those available) for determining the severity of illness, potential for hypoxemia and nature of illness that may influence level of concern for hypoxemia (and hence likelihood of pulse oximeter use) and use of oxygen (Shaded boxes occur on first day of admission; components in bold are included in these analyses; page i has list of abbreviations)

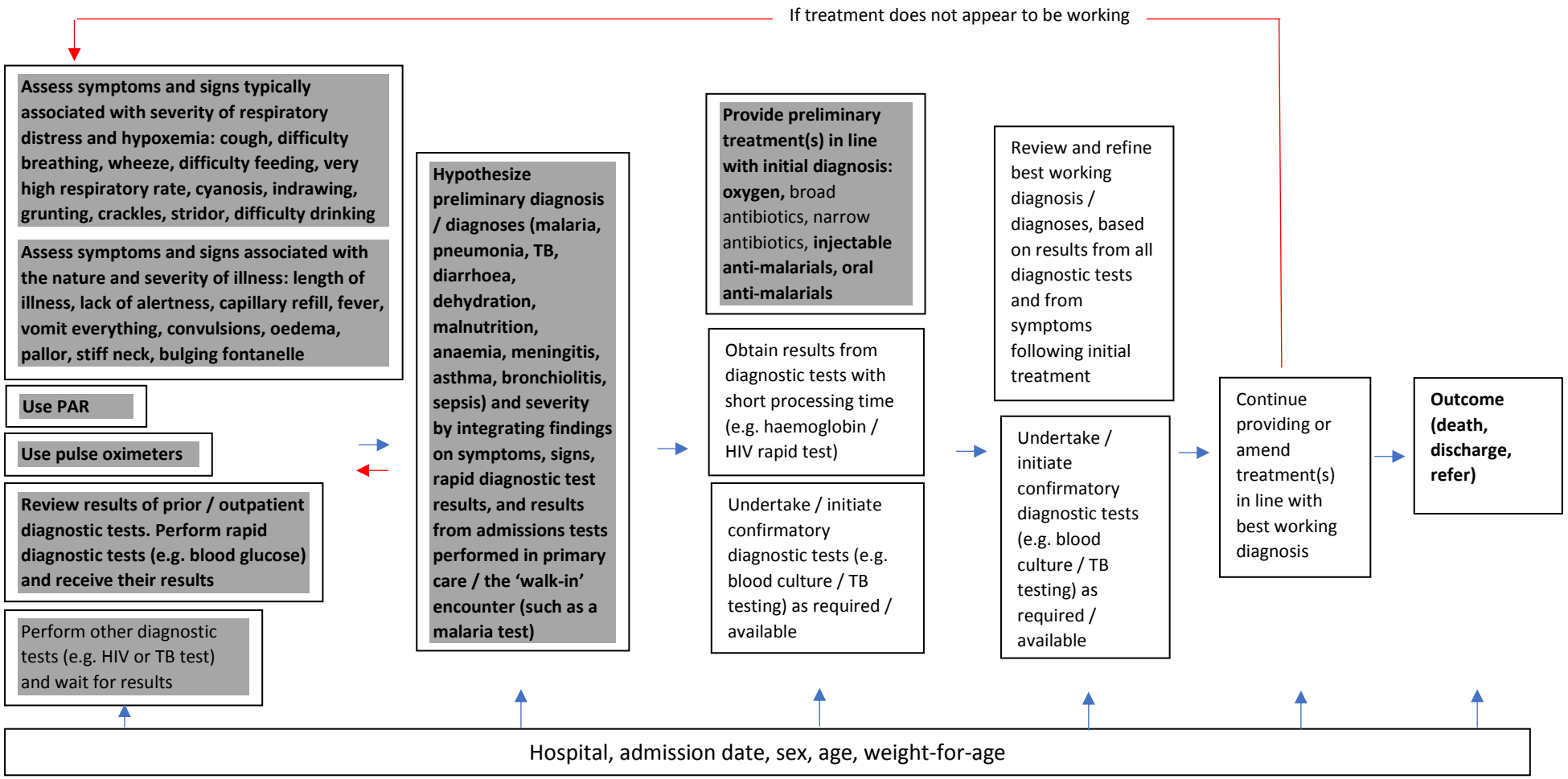
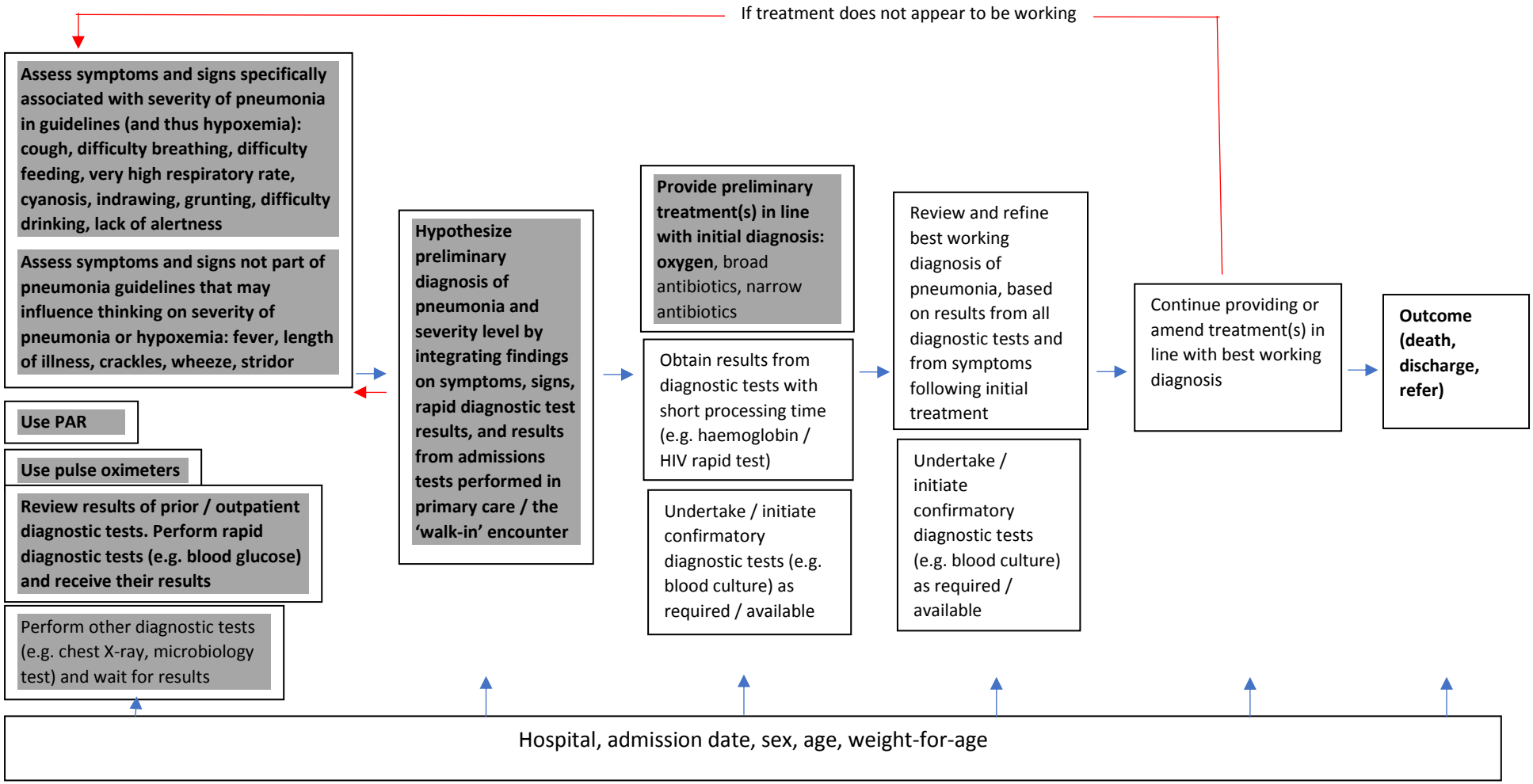


Figure 3.3c: Conceptual diagram of clinical process in children with preliminary diagnosis of pneumonia, with the most relevant variables (from those available) for determining the diagnosis and severity specifically of pneumonia and that may influence the level of concern for hypoxemia (and hence likelihood of pulse oximeter use) and use of oxygen (Shaded boxes occur on first day of admission; components in bold are included in these analyses; page i has list of abbreviations)



3.5 Data source, participants and variables

3.5.1 Clinical Information Network dataset variables

I obtained CIN data for 74 variables. (Appendix 3.3 lists these.) Only variables with less than 40% missing data were included in the analyses. (Section 3.9.2 explains rationale)

3.5.2 Defining the study population

I included data from admissions between September 2013 (the start of CIN data collection) and February 2016, inclusive, for children aged one month to 12 years. Children under one month were excluded because they have different health issues and treatments than children above one month [WHO,2017a]; patients over 12 years were excluded to focus on children, not adolescents, and because many Kenyan paediatric wards do not admit children older than 13.

Data were included from seven CIN hospitals for the descriptive and regression analyses; these hospitals were chosen because they were the ones at which pulse oximeters were used with at least 20%[2] of children on average from September 2013-February 2016; hospitals with lower rates of pulse oximeter use were excluded to ensure that enough data on pulse oximeter use were available for the analyses. (Figure 3.1 shows pulse oximetry levels for all 14 CIN hospitals over the study time period; Appendix 5.2 has a table of each hospital's average level of pulse oximeter use.)

[2] This threshold was chosen because it was a natural cut-off between the hospitals where pulse oximeters are rarely if ever used, or where uptake occurred very late in the study's time-period, and hospitals where pulse oximeters are used with at least a substantial subset of children.

These public (district) hospitals are all first referral centres, located in five different counties. They have paediatric ward capacities of 30-60 beds and have 1,300-3,000 paediatric admissions per year. 20-50% of their catchment area populations live in extreme poverty.[Ayieko et.al.2016]

In total, 27,906 child admissions were included in the analyses, ranging from 2,700 to 5,700 admissions per hospital.

3.6 Ethics

3.6.1 Data Management Plan

I created a Data Management Plan (see Appendix 3.4) to detail the safe storage and backup of the data, how the children's identities would be kept anonymous, and how the data and results would be archived and shared.

3.6.2 Ethical approval

KEMRI has a research and ethics committee which provides ethical approval for research conducted by its researchers, such as the data collection through this CIN dataset.[KEMRI,n.d.; English,2015] KEMRI provided ethical approval for collection of the dataset. The ethical committee provided an exemption from having to obtain individual consent for the collection of these data because they are collected from medical records documented only after the child is discharged, the data are anonymized, and have minimal/less than minimal risk.[English,2015] My DPhil supervisor, Professor Mike English, is the Principal Investigator on the main project for which the CIN data have been collected. When the annual request for renewal of the research

committee's approval of this data was undertaken in April 2015, I was added as a co-investigator with a specific role to analyse some of the data. The KEMRI Data Governance Committee also approved my data sharing agreement application, thereby enabling the data to be transferred to me. Furthermore, I applied for and received approval from the Oxford University CUREC ethical committee to use the dataset's data for my research. (Appendix 3.5 has these approval confirmation letters.)

3.7 Statistical analysis program

I used the R statistical program[The R Foundation] for these analyses.

3.8 Cleaning and organising the data and creating new variables

3.8.1 Challenges

The numerous challenges associated with cleaning and organising large datasets of real-world data collected from medical records, i.e. not collected for research, have been described elsewhere.[Cai&Zhu,2015, Chen et.al.2014, Jensen et.al.2012, Cohen et.al.2015, Wyber et.al.2015] The process of cleaning the large CIN dataset (74 variable measurements for each of 60,355 child admissions to 14 hospitals) to prepare it for use in this research took more than six months. This was carried out in R and Microsoft Excel. The database was created from extracting data from medical records. Preparing the data for the planned analysis required dealing with some issues of data quality, for instance, removing impossible values (e.g. dates before the

dataset began) and adjusting values based on other variables' additional or contradictory information (e.g. changing "vomit everything" values from "NA" to "no" when "vomit" value was "no") [Cohen et.al.2015; Cai&Zhu,2015]; and adapting the dataset for the purposes of the research by, for example, creating and recoding new variables, and removing individuals who did not fulfil the inclusion criteria [Jensen et.al.2012; Cohen et.al.2015; Chen et.al.2014].

Examples of particularly problematic challenges concerned the variables that described the children's age and diagnosis. In the original data that I obtained from the CIN dataset, the children's age was provided in three variables: *Age in years*, *Age in months*, and *Age less than one month* (this variable was dichotomous with values of yes or no). These variables were not always consistent and required careful checking. (Appendix 3.6 and 3.7 have an explanation of the process developed to apply a systematic method of recording.)

In terms of the diagnoses, I obtained 36 admission diagnoses variables from the original CIN dataset; these included dichotomous variables specifying whether a child had a particular diagnosis, e.g. pneumonia, and other more open variables, for the primary diagnosis, secondary diagnosis etc. Sometimes International Classification of Diseases (ICD-10)[WHO,2016a] codes were given for these diagnoses which helped with the classification's specificity and objectivity, but often the diagnoses were written in free form text, using different spellings, specifying different aspects/types of the diagnosis, sometimes adding comorbidities and/or origins of the condition, etc. As a result, there were thousands of different variations in diagnoses recorded; for example, within this dataset, there were more than 200 variations in how sepsis was listed (Appendix 3.8 contains each listing for each of the 11 diagnoses of interest). I read through each diagnosis data entry (several thousand) and classified each as one of the 11 diagnoses of interest, or to an 'other' category, and then wrote coding to create new dichotomous variables for the 11 diagnoses of interest which specify the presence/absence of the diagnosis for each child, based on the original listings.

More details on new variable creation and dichotomisation are found below. Table 3.3 describes all variables included in the quantitative analyses; Appendix 3.6 contains information on what was done to/with each variable and why; Appendix 3.9 lists the detailed R codings for the cleaning and organising process (and for the later multiple imputation and regressions).

3.8.2 Creation of new variables

Table 3.1 shows the new variables created using existing variables, why and how.

Table 3.1: New variables created using existing variables

New variable	**Why created**	**How created**
Admission month	Pulse oximeter and oxygen use might vary by admission month because diagnoses could vary by month based on seasonality, and health practices could also vary by month depending on HCW rotations. In addition, health information recording quality could vary by month because of holidays taken by HCWs and data clerks.	By extracting the month from the original admission date variable
Admission time period	Pulse oximeter use and other practices could have changed over time because of general improvements over time, events such as guideline introductions, increased familiarity with the CIN and its recording system and recommendations, and the build-up of CIN feedback.	Admission was coded according to the 6-month interval in which the admission date occurred, from September 2013 through February 2016.
Weekend admission	Available healthcare might be reduced on weekends when there are fewer staff.	By extracting the day of the week from the original admission date variable
Weight-for-age	I wanted to control for a malnutrition measure in the regressions. I could not use the original CIN dataset's mid-upper arm circumference variable, because almost all	•Divided the original weight variable by the age of the child •Compared this with:

	of its values were missing, so I adapted the dataset's *Weight* variable to take into account its relation with age, thus creating a *Weight-for-age* variable.	○the z scores of the reference data from the WHO's Multicentre Growth Reference Study (for children aged 1 month to 10 years)[WHO,n.d.a; WHO,n.d.b; WHO,n.d.d] ○the Canadian Paediatric Endocrine Group (who extended the WHO's weight-for-age reference values to 11-19 year olds through modelling)[Rodd et.al.2014]. •Used the Canadian Paediatric Endocrine Group's statistical program[CPEG,n.d.] to carry out these calculations and produce a weight-for-age value for each child.
Diagnoses variables	I identified eleven diagnoses to include in the regression analyses (pneumonia, malaria, TB, diarrhoea, dehydration, malnutrition, anaemia, meningitis, asthma, bronchiolitis and sepsis), which are associated with hypoxemia and/or are common diagnoses in this setting.[WHO,2014b; Ayieko et.al.2016] In addition, the pneumonia variable was necessary for running regressions specifically with children with pneumonia.	In the original dataset, there were 36 variables providing diagnoses information (see Appendix 3.3). I used the thousands of listed diagnoses within these 36 variables to create new individual variables for each of the 11 diagnoses of interest. (See Appendix 3.8).
Antimalarials	The original dataset included four variables indicating which antimalarials, if any, children received. I wanted to control for antimalarials in some of the regressions, as a measure of illness severity, but I did not need the detail of antimalarial type; knowing whether the child was given an oral vs. injectable antimalarial was useful, however, as guidelines recommend giving injectable rather than oral antimalarials in severe cases [Kenyan MoH,2016], and thus a HCW may think of a child as more ill if they have received an injectable antimalarial, which may impact other	I recoded the original variables of antimalarial types to one new *Antimalarials* variable, with 3 values: 'inject', 'oral', or 'neither'.

	treatment decisions (e.g. concerning oxygen provision).	
Hospital use of pulse oximeters by admission month[i]	Levels of pulse oximeter use vary both across and within hospitals, and this is likely to affect individual HCWs' use of pulse oximeters. For example, it is possible that a child's signs and symptoms might be less influential on HCWs' decision to use a pulse oximeter if pulse oximeters are routinely used in that setting. I therefore controlled for the relative level of pulse oximeter use at the hospital during the month of admission.	To do so, I created a variable in which children were given values of 'low', 'medium low', 'medium high', or 'high', depending on if pulse oximeters were used with 0-20%, 21-50%, 51-80%, or 81-100%, respectively, of children in the hospital and month of their admission.

[i] The *Hospital use of pulse oximeters by admission month* variable was created using the *Admission month*, *Pulse oximeter use*, and *Hospital* variables, all three of which were included in the multiple imputation process (see Section 3.10). For this reason, the *Hospital use of pulse oximeters by admission month* variable was created after the multiple imputation process, to avoid the multicollinearity that would have occurred if all four variables were included during multiple imputation. This multicollinearity was not a concern for the regressions because the *Admission month* variable was not included in the regression models (*Admission month* was included in the multiple imputation because it was shown to influence the data's missingness levels – see Section 5.4.1).

3.8.3 Dichotomization of variables

i) Symptom variables

Most symptom variables were dichotomous; and I dichotomized the few categorical symptom variables (*Very high respiratory rate*, *Oedema*, *Pallor*, *Lack of alertness*, and *Capillary refill*), to avoid using categorical variables in the regression analysis. I judged that this dichotomization was not likely to cause a loss of valuable information as I was interested in whether the symptom was present vs. not present or severe vs. not severe, rather than the symptom's gradation or nuance.

A value of '1' was used to show when a symptom was present or severe. Table 3.2 shows the values changed to '1' vs '0' for each symptom.

Table 3.2: How symptoms with more than two original categories were dichotomized

Symptom	Value(s) changed to '1'	Value(s) changed to '0'	Value(s) changed to 'NA'
Fever, Cough, Difficulty breathing, Vomit everything, Difficulty feeding, Convulsions, Stridor, Central cyanosis, Chest indrawing, Grunting, Wheeze, Crackles, Difficulty drinking, Stiff neck, Bulging fontanelle	'Yes', i.e. the symptom was present	'No', i.e. the symptom was not present	
Very high respiratory rate	A very high respiratory rate (defined as >70 for children aged 1-11 months, >60 for children aged 1-4 years, and >45 for children aged 5-12 years)[i]	A low or normal respiratory rate	
Oedema	'Face', 'Foot', or 'Knee'	'None'	
Pallor	'+' (mild or moderate) or '+++' (severe pallor)	'None'	
Lack of alertness	'Verbal response', 'Pain response' or 'Unresponsive'	'Alert'	'Other scale'
Capillary refill	Any value greater than '3 sec'(seconds)[ii]	Any value of '3 sec' or less	'indeterminate'

[i] These thresholds were chosen because roughly 15% of children in the dataset in each of these age brackets had respiratory rates above these levels. These thresholds are justified given that: in their study on Kenyan children with acute lower respiratory infections, Onyango et.al.(1993) found that a respiratory rate of ≥70 was one of the three best clinical indicators for hypoxemia in children 3-11 months old, and that a respiratory rate of ≥60 was the most accurate indicator of hypoxemia in children 1-3 years old; the WHO's Pocket Book of Hospital Care for Children recommends that oxygen be given when the respiratory rate is ≥70; and in Fleming et.al.(2011)'s systematic literature review, normal respiratory rates dropped from birth through to age 18. These thresholds are higher than the WHO's thresholds for detection of pneumonia[WHO,2013] because I wanted a variable that captured a more severe illness presentation.

[ii] This threshold was used because the Kenyan Basic Paediatric Protocols classifies a capillary refill of >3 seconds as an emergency sign to look for when triaging children.[Kenyan MoH,2016]

ii) Pulse oximeter value variable

I also dichotomized the *Pulse oximeter value* variable, to examine whether HCWs are using pulse oximeters in the ways recommended by the WHO and the Kenyan Basic Paediatric Protocols, namely that oxygen should be given when children have pulse oximeter readings of <90%. [WHO,2014b; Kenyan MoH,2016] Therefore, children were given a '1' if their original variable's value was <90%, and a '0' if their original variable's value was ≥90%.

At the end of the data cleaning and management I had a dataset of 45 variables, which Table 3.3 lists and describes.

Table 3.3: Variables included in the quantitative analyses

Variable	Type	Class	Description
Pulse oximeter use	Diagnostic tool	Binary	Whether a pulse oximeter reading was taken
Pulse oximeter value	Diagnostic tool	Binary	Oxygen saturation of <90% vs. ≥90%
Oxygen use	Treatment	Binary	Whether oxygen was given
Admission month	Demographic	Non-ordered categorical	The month that the child was admitted
Weekend admission	Demographic	Binary	Whether the child was admitted on a weekend vs. weekday
Admission time period	Demographic	Ordered categorical	Time periods: Sept 2013-Feb 2014, March 2014-Aug 2014, Sept 2014-Feb 2015, March 2015-Aug 2015, Sept 2015-Feb 2016
Hospital	Demographic	Non-ordered categorical	Hospital where child was admitted (n=7)
Sex	Demographic	Binary	Female, male
Hospital use of pulse oximeters by admission month	Demographic	Ordered categorical	The level of pulse oximeter use at the hospital during the month of admission: 0-20% (low), 21-50% (medium low), 51-80% (medium high), 81-100% (high)
Age in years	Demographic	Continuous	Age in years (0-12)
Weight-for-age	Demographic	Continuous	Weight-for-age value
Paediatric Admission Record (PAR)[i] *use*	Recording	Non-ordered categorical	The PAR form was not available vs. PAR available but not used vs. PAR used
Length of illness before admission	Demographic	Ordered categorical	Number of days of illness before admission (0-4+)
Fever	Symptom	Binary	Whether had fever
Cough	Symptom	Binary	Whether had cough
Difficulty breathing	Symptom	Binary	Whether had difficulty breathing
Vomit everything	Symptom	Binary	Whether was vomiting everything
Difficulty feeding	Symptom	Binary	Whether had difficulty feeding
Convulsions	Symptom	Binary	Whether had convulsions

Very high respiratory rate	Symptom	Binary	Whether had a very high respiratory rate
Oedema	Symptom	Binary	Whether had oedema
Stridor	Symptom	Binary	Whether had stridor
Central cyanosis	Symptom	Binary	Whether had central cyanosis
Chest indrawing	Symptom	Binary	Whether had chest indrawing
Grunting	Symptom	Binary	Whether was grunting
Wheeze	Symptom	Binary	Whether was wheezing
Crackles	Symptom	Binary	Whether had crackles
Capillary refill	Symptom	Binary	Capillary refill time (>3 vs. ≤3 seconds)
Pallor	Symptom	Binary	Whether had pallor
Lack of alertness	Symptom	Binary	Whether alert vs. verbal response, pain response or unresponsive
Difficulty drinking	Symptom	Binary	Whether had difficulty drinking
Stiff neck	Symptom	Binary	Whether had a stiff neck
Bulging fontanelle	Symptom	Binary	Whether had bulging fontanelle
Diagnosis pneumonia[ii]	Diagnosis	Binary	Whether had pneumonia
Diagnosis malaria[ii]	Diagnosis	Binary	Whether had malaria
Diagnosis TB[ii]	Diagnosis	Binary	Whether had TB
Diagnosis diarrhoea[ii]	Diagnosis	Binary	Whether had diarrhoea
Diagnosis dehydration[ii]	Diagnosis	Binary	Whether had dehydration
Diagnosis malnutrition[ii]	Diagnosis	Binary	Whether had malnutrition
Diagnosis anaemia[ii]	Diagnosis	Binary	Whether had anaemia
Diagnosis meningitis[ii]	Diagnosis	Binary	Whether had meningitis
Diagnosis asthma[ii]	Diagnosis	Binary	Whether had asthma
Diagnosis bronchiolitis[ii]	Diagnosis	Binary	Whether had bronchiolitis
Diagnosis sepsis[ii]	Diagnosis	Binary	Whether had sepsis
Antimalarials[iii]	Treatment	Non-ordered categorical	Whether given injectable antimalarials, oral antimalarials, neither

Outcome	Outcome	Non-ordered categorical	Alive, dead, referred, other

[i] The Paediatric Admission Record (PAR) is an admissions form used to record medical information; it was implemented to improve recording of this information and to prompt recommended behaviour [Gachau et.al.2017]

[ii] These diagnoses variables indicate whether the HCW classified the child as having any type of the particular diagnosis at admission, even if they were also classified as having another/other diagnosis(es). Based on advice from key informants familiar with the Kenyan hospital setting, it was assumed that if a diagnosis was not listed, then the HCW who recorded this information did not assess the child as having the diagnosis, i.e. this variable had no missing data.

[iii] Based on advice from key informants familiar with the Kenyan hospital setting, it was assumed that antimalarial 'NA' values indicated the treatment was not given, because as part of the prescription process, HCWs record all treatments provided; thus this variable had no missing data.

3.9 Descriptive analyses

3.9.1 Basic descriptive statistics

I calculated and plotted the proportions of the 45 variables; of stratifications, e.g. *Diagnosis pneumonia* stratified by *Admission month*, *Pulse oximeter use* by *Hospital* over time; and the relationship between each variable and *Pulse oximeter use*, *Oxygen use* and *Pulse oximeter value*, for example, the percentage of males who did/did not obtain oxygen vs. the percent of females who did/did not obtain oxygen, to better understand the data's distribution and the relationships between variables.

3.9.2 Missing data patterns

I then explored the dataset's missing data patterns.

I first calculated the amount of missing data for each variable and tabulated these values. As mentioned above, any variables with more than 40% missing data would be excluded from the analyses; this is because imputing large amounts of missing data may bias the results as multiple imputation works by estimating the missing data from the existing data, so the less existing data available, the less reliable the missing data estimate. Other studies have also used the 40% cut-off.[Deng et.al.2016]

I calculated and plotted the number of missing values per person and created a histogram displaying this information. I also examined whether the children with missing data were different than the children without missing data by comparing the means (for continuous

variables) and the proportions (for categorical variables) of the complete cases (the children with no missing data) vs. the children with some missing data.

3.10 Multiple imputation

3.10.1 Rationale

Missing data is problematic because it reduces the analyses' power, and also, the missing values may be more likely to be present in one variable value than another, and therefore if included, could change the results. For example, if older children had more missing values than younger children then results for analyses that involve age as an explanatory, response or confounding variable, would likely yield different results if only the data from children with complete data were included (and thus the younger children were over-represented) than if data for all children were available and so could be included; this would especially be the case if the reason for why older children had more missing data in this hypothetical situation also affected the outcome variable, e.g. if doctors provided more detailed care (including diagnostic testing and recording) for younger than older children.

Various methods exist for dealing with missing data. The simpler methods, e.g. inserting the group's mean into each missing data value, can introduce substantial bias depending on the amount of missing data, and do not take into account the uncertainty of the imputed value.[Sterne et.al.2009]

Multiple imputation is a process by which missing values are predicted based on existing values, through an iterative process using a Bayesian approach. The imputed values will always be

estimates, not the real values; to take this uncertainty into account, various imputed datasets with different estimated values are produced, thus incorporating variability into the process. The results of analyses conducted with the group of imputed datasets are then combined using Rubin's rules.[Sterne et.al.2009]

3.10.2 Exploration of missing data reasons: MCAR vs. MAR vs. MNAR

i) What are MCAR, MAR and MNAR and why is the distinction important?

Missing data can be Missing Completely at Random (MCAR), Missing at Random (MAR) or Missing Not at Random (MNAR). If data are MCAR then the missing values do not differ systematically from the available values because the reason for the missing values being missing was not related to the actual values of the missing data.[Sterne et.al.2009] An example would be if a thermometer breaks and so no temperature measurements are recorded that day.

If data are MAR then a systematic difference between the missing and available data exists but is known, from previous studies, knowledge of the topic or population, or from the study's available data.[Sterne et.al.2009] For instance, perhaps a study is examining the living conditions of people of different ethnicities in a community, and it is known from previous studies that in this particular population, people of certain ethnicities are more likely to leave a survey question about income level or age (two variables of interest in the study) blank. So if ethnicity is known, the missing values are predictably informed by existing data.

If data are MNAR then a systematic difference between the missing and available data exists but is not known.[Sterne et.al.2009] For example, participants in a drug's clinical trial may be less likely to come in for a measurement appointment if they experience strong side effects.

In order to carry out multiple imputation, the data need to either be MCAR (it is rare that missing data are MCAR; complete case analyses implicitly assume data are MCAR, which is often

an inaccurate assumption) or MAR; carrying out multiple imputation with MNAR data will bias the results because the multiple imputation process cannot take into account the reasons for the missingness while predicting the values, whereas if the data are MAR then the factors influencing the missing data levels can be included in the multiple imputation process, and so can be taken into account in the process.[Sterne et.al.2009]

ii) Determining whether the data are MAR vs. MNAR

To determine if the data were MAR rather than MNAR, and if so which variables influenced the likelihood of missing data, I investigated whether missingness was more likely for certain values of particular variables than for other values of these variables.

I had previously created a variable which gave a score to each child for how many missing variables they had. These scores were averaged out to create a mean number of missing variables across the children.

In addition to age and sex, which are routinely examined, I considered whether the data's missingness levels were potentially influenced by the following variables, chosen based on topic knowledge and through speaking to people involved with data collection:

- *Admission month*: data clerks who transfer the medical records data into the CIN are on leave in July and December, and staff turnover occurs in particular months
- *Weekend admission*: fewer staff are on shift on the weekend so recording may be less thorough then
- *Admission time period*: recording probably improved over time as data clerks became more familiar with the CIN system, and HCWs received more feedback from the CIN on recording medical information

- *Hospital*: in different hospitals, different systems may be in place for recording medical information and monitoring this recording, and attitudes concerning medical record-keeping may differ
- *Paediatric Admission Record use*: this is an admissions form used to record medical information; it was implemented to improve recording of this information and to prompt recommended behaviour [Gachau et.al.2017] (as it provides boxes/pages in which to enter specific information); therefore, one would expect that missing data would be less common when the form is used
- *Outcome*: all data are recorded into the dataset after the child is discharged, referred or dies; retrospective recording may be less thorough if the child dies or is referred than if the child recovers

I also tested the *Pulse oximeter use* and *Oxygen use* variables as it may not be possible to run multiple imputation if the outcome variable influences the missing data levels.

To test which if any of these variables influenced the missing data levels, I first calculated the mean number of missing variables per child for each value of each variable (e.g. the mean number of missing variables of males vs. the mean number of missing variables of females); I graphed this relationship and then tested whether the difference between these values was significant ($p<0.05$), through Chi-squared analyses for the categorical variables, and regression for the *Age in years* continuous variable. If a significant difference was found, this would indicate that the variable(s) were associated with the data's missingness levels; the dataset's missingness could then be considered MAR and the variable(s) in question would need to be included in the multiple imputation process, so that its/their influence could be taken into account in the prediction of the missing values.

3.10.3 Variables for inclusion

I carried out the multiple imputation process separately for each regression's set of variables, to avoid multicollinearity. This is because, carrying out one multiple imputation process that included all variables needed for all analyses would have meant including variables with similar missingness patterns, such as *Pulse oximeter use* and *Pulse oximeter value* (*Pulse oximeter value* must have had a missing value each time that *Pulse oximeter use* did).

In the multiple imputation process, I included all variables that I planned to include in the regression, and any additional variables likely to affect missing data levels (see Section 3.10.2.ii).

3.10.4 Statistical analysis program

There are various statistical programmes available for carrying out multiple imputation. I used the 'mice' programme in R. Mice uses a fully conditional specification (FCS) Multivariate Imputation by Chained Equations (MICE) approach, described in Box 3.2.[van Buuren&Groothuis-Oudshoorn,2011] The coding used for the multiple imputation is shown in Appendix 3.9.

Box 3.2: the MICE process [White et.al.2011]:

- Values are entered in for the missing values by simple random sampling, with replacement, from the existing values.
- Variable A, the first variable with missing data, is regressed on the other variables of the dataset but only using the data from individuals who have existing, non-missing, values for variable A.
- Values are entered in for the missing values of variable A by drawing from this resulting regression distribution (the posterior predictive distribution).
- The next variable with missing data, Variable B, is regressed on the other variables of the dataset but only using the data from individuals who have existing, non-missing, values for variable B. The imputed values of Variable A are included in this process.
- Values are entered in for the missing values of variable B by drawing from this resulting regression distribution.
- These steps are carried out for each variable until values have been imputed for all variables that have missing values.
- This constitutes one cycle. Multiple cycles are run to produce one imputed dataset (I ran five cycles per imputed dataset in my analyses)
- This process is repeated multiple times to produce multiple imputed datasets. See Section 3.10.5 below for information on how I determined the number of imputations to produce in these analyses, based on estimating when convergence occurs.

In mice one can specify the univariate imputation model used for each variable in the above process. In these analyses I used predictive mean matching for the numerical variables (in predictive mean matching, only values within the range exhibited by the existing data will be imputed, which is useful when values outside of this range would be impossible, e.g. negative numbers for *Age in years*), logistic regression for the dichotomous variables, multinomial logit model for the unordered categorical variables with more than two levels, and ordered logit model for the ordered categorical variables with more than two levels.[van Buuren&Groothuis-Oudshoorn,2011]

3.10.5 Number of imputations

There is no consensus on how many imputations are necessary for multiple imputation. Rubin, who, in 1977, was the first to describe multiple imputation, developed a formula for the relative variance, or efficiency, given the level of missing data and the number of imputations used: (1+ λ/K) where λ = the amount of missing data and K = the number of imputations.[Carpenter&Kenward,2007; Rubin,1977; Rubin,1987] Thus when five imputations are run with a dataset with 50% missing data, according to the formula the standard deviation would only be 5% wider than if an infinite number of imputations were computed, as √(1+ 0.5/5) = 1.049. [Schafer,1999] Rubin used this formula to argue that only 3-5 imputations are ever necessary.[Graham et.al.2007] Schafer(1999) used similar logic to argue that no more than 10 imputations are needed, except for very high missing data levels. Graham et.al.(2007) took a different approach by using a Monte Carlo simulation to show that regardless of the number of imputations, regression coefficients are not biased, but running fewer imputations results in larger standard errors and reduced power. Furthermore, Bodner(2008) and White et.al.(2010) concluded, based on their simulations, that the number of imputations should roughly match the % of missing data. Moreover Horton&Lipsitz(2001) argue that one can informally ascertain the suitable number of imputations by creating multiple groups of imputations and evaluating whether the groups' estimates are consistent.

I therefore carried out 10 and 30 imputations (Appendix 3.9 contains the R coding) and compared the coefficients and confidence intervals produced from running the regression models with the 10 vs. 30 imputed datasets. In addition, I created graphs of the mean and standard deviation for all variables across the iterations of the 30 imputations to examine the variability across imputations. I also calculated the overall % of missing data for each of the three regressions' collections of variables. I used these analyses' results and the above literature's advice, given the missing data levels for each regression's collection of variables, to decide whether 10 imputations was sufficient or if 30 (or more) should be used instead.

Box 3.3 shows further sensitivity analyses conducted to check for bias in the imputed data due to violation of the MAR assumption.

Box 3.3: Checking for bias in the imputed data due to violation of MAR assumption

If factors with substantial influence on the data's missingness are not included in the imputation process, the data can become biased, but it is not possible to know for sure whether all factors influencing the levels of missing data have been taken into account. It is therefore necessary to look for this bias in the imputed datasets. I did so in three ways:

- I checked the means of the continuous variables, and the proportions of the three categorical variables with the largest amount of missing data, for each of the imputed datasets from the 11th imputation through the 30th imputation carried out for the first regression, to ensure that the multiple imputation process was accurately estimating the missing values in a manner that retained the characteristics of the existing data.

- I compared the means (for continuous variables) and proportions (for categorical variables) using the complete case dataset (in which only the children without any missing data were included) vs. the imputed datasets, and graphed these differences.

- I compared the coefficients and confidence intervals produced from running the regression models using the complete case vs. imputed datasets. Although some differences would be expected between the complete case and imputed results, any substantial differences would suggest that the multiple imputation process may have biased the results.

3.11 Logistic regression

I used logistic regression because the outcomes of interest are both dichotomous variables (children either obtained or did not obtain a pulse oximeter reading/oxygen), and odds ratios can be easier to interpret than regression coefficients.

3.11.1 Background on logistic regression

I used logistic regression for these analyses to obtain a best fitting model for describing the relationship between my dichotomous outcomes of interest (pulse oximeter use and oxygen use) and various explanatory variables. Background information on logistic regression is shown in Box 3.4.

Box 3.4: Background on logistic regression

The basic logistic regression equation is shown by: $\text{Log}[p/(1-p)] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots \beta_m x_m$

Where p is the *probability* of the outcome of interest, and therefore [p/(1-p)] is the *odds* of the outcome of interest, and Log[p/(1-p)] is the *log odds* of the outcome of interest; β_0 is the intercept term, and $\beta_m x_m$ is the coefficient of the x explanatory variable. [Sperandei,2014]

Thus, for instance, the equation I am using for Research Question 1 is:

$\Pr(\text{Pulse oximeter use}) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots \beta_m x_m$

Where $\beta_m x_m$ are the coefficients of the x demographic and symptom variables I am controlling for or investigating.

This logit transformation is performed, and hence *log odds* is produced instead of *probability*, because *probability* can only range from 0 to 1 whereas *log odds* can range from negative infinity to positive infinity, and it is easier to model a variable with an infinite range. There are other transformations that can be performed that similarly increase the range, but the logit transformation is the one that is generally used as it is arguably the easiest to interpret. [UCLA,n.d.]

So, by inserting the intercept term value and the coefficient values for each of the explanatory variables into the above equation, it is possible to calculate the *log odds* of the outcome of interest.

And to obtain the *odds* of the outcome of interest, one takes the exponential of the *log odds* calculated above.

So, to obtain the *odds* of the outcome of interest for the reference/baseline population (the population against which the population with the exposures of interest is compared), one uses the following equation: $\text{Odds} = \exp(\beta_0)$

To obtain the *odds* of the outcome of interest for the population with a reference/baseline value for the x_1 explanatory variable but a non-reference value for the x_2 explanatory variable, you would use the following equation: $\text{Odds} = \exp(\beta_2 x_2) \times \exp(\beta_0)$

And to obtain the *odds* of the outcome of interest for the population with non-reference values for x_1 and x_2 explanatory variables, you would use the following equation: $\text{Odds} = \exp(\beta_1 x_1 + \beta_2 x_2) \times \exp(\beta_0)$

The coefficient β_1 is the log of the *odds ratio* between the x_1 population and x_1's baseline population. So, to obtain the *odds ratio* of the x_1 explanatory variable, one uses the following equation: $\text{Odds ratio} = \exp(\beta_1 x_1)$

By subtracting the *odds ratio* from 1 (if the *odds ratio* is less than 1) or subtracting 1 from the *odds ratio* (if the *odds ratio* is greater than 1) one can determine the % less (if the *odds ratio* is less than 1) or the % more (if the *odds ratio* is greater than 1) likely that the outcome of interest is to occur if x_1 is true compared to if x_1's baseline is true.

The *odds ratio* indicates the likelihood of the outcome of interest for a specific group compared to the reference group, whereas the *probability* indicates the likelihood of the outcome of interest for the specific group. [Sperandei,2014]

3.11.2 Statistical programme and coding used

I carried out the regressions in the R statistical program, specifically using the 'mice' package. I used this package because of its relatively extensive regression functions, e.g. when a group of imputed datasets is loaded into mice, it recognizes that it is a collection of datasets rather than a single dataset, and then can run regressions and other analyses accordingly (e.g. the regression is run on each imputed dataset and the results are averaged using Rubin's rules to provide a pooled summarized result).[van Buuren&Groothuis-Oudshoorn,2011] Appendix 3.9 has the regressions' coding. I used the binomial family for running these regressions because the outcome variables of interest are binary variables describing a finite number of discrete events.

3.11.3 Full logistic regression models

i) Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

In the full model for this regression question, I controlled for 7 demographic variables, and included 2 other demographic variables, 20 symptoms and 15 two-way interactions, so, with *Pulse oximeter use*, a total of 45 variables.

Table 3.4 lists these variables and why they were included in this regression's full model; Table 3.5 lists the variables included in Research Question 1 and 2.

The included symptoms were chosen because they are:

- Respiratory symptoms: HCWs might choose to use pulse oximeters with children with particular respiratory symptoms that they think might indicate an oxygen need

  And/or

- Symptoms indicating particular non-respiratory diagnoses: HCWs might recognize that oxygen may be needed for children with non-respiratory conditions OR HCWs may think there is no point using a pulse oximeter with children with non-respiratory conditions

  And/or

- Danger signs or other symptoms indicative of illness severity: HCWs might choose to use pulse oximeters with children who they believe to be severely ill

These choices of symptoms were validated by consultation with paediatricians and other HCWs.

Note: the qualitative data collection of this thesis was carried out after the quantitative data analysis so the choice of variables in these regressions was not informed by the qualitative research, but the qualitative research was informed by the quantitative data analyses findings.

Table 3.4: Variables included in regression 1's full model and why

Variable	**Type**	**Why it was included**
Pulse oximeter use	Outcome of interest	Outcome of interest
Weekend admission	Explanatory	Care may be reduced on a weekend when there are fewer staff available
Admission time period	Control	Pulse oximeter use could have changed over time because of general improvements over time, events such as guideline introductions, and the build-up of CIN feedback
Hospital	Control	Varying hospital characteristics e.g. concerning resource availability, management structures and staffing, differences in illness and socioeconomic profiles of patients etc. could cause differences in care
Sex	Control	Pulse oximeters might be used more commonly with males or females
Hospital use of pulse oximeters by admission month	Control	The reasons for pulse oximeter use may be different depending on whether at that hospital at that time, pulse oximeters are used commonly or not.
Age in years	Control	Younger children may be seen as more vulnerable and so in greater need of a pulse oximeter reading

Weight-for-age	Control	An indication for malnutrition; could impact HCWs' views on diagnosis and illness severity
Paediatric Admission Record (PAR) use[i]	Control	HCWs might stick to guidelines more closely when using the PAR
Length of illness before admission	Explanatory	An indication of illness severity
Fever	Explanatory	A common symptom
Cough	Explanatory	A respiratory symptom
Difficulty breathing	Explanatory	The literature suggests this is one of the best clinical signs for indicating hypoxemia[a]
Vomit everything	Explanatory	-General danger sign[b] (could prompt pulse oximeter use) -Non-respiratory symptom associated with severe illness (could discourage pulse oximeter use)
Difficulty feeding	Explanatory	-An indication of illness severity -The literature suggests this is one of the best clinical signs for indicating hypoxemia[a]
Convulsions	Explanatory	Danger sign[b,c]
Very high respiratory rate	Explanatory	-An indication of respiratory illness severity -The literature suggests this is one of the best clinical signs for indicating hypoxemia[d]
Oedema	Explanatory	Danger sign indicative of severe acute malnutrition[b]
Stridor	Explanatory	Danger sign indicative of severe pneumonia[b]
Central cyanosis	Explanatory	-Danger sign[c,e] -An indication of respiratory illness severity -The literature suggests this is one of the best clinical signs for indicating hypoxemia[a,f]
Chest indrawing	Explanatory	-An indication of respiratory illness severity -The literature suggests this is one of the best clinical signs for indicating hypoxemia[a,f]
Grunting	Explanatory	-An indication of respiratory illness severity -The literature suggests this is one of the best clinical signs for indicating hypoxemia[a,f]
Wheeze	Explanatory	Respiratory symptom
Crackles	Explanatory	-The literature suggests this is one of the best clinical signs for indicating hypoxemia[d]
Capillary refill	Explanatory	Danger sign[c,e]
Pallor	Explanatory	Danger sign indicative of anaemia[b]
Lack of alertness	Explanatory	-Danger sign[b,c] -An indication of illness severity -The literature suggests this is one of the best clinical signs for indicating hypoxemia[d]
Difficulty drinking	Explanatory	-General danger sign[b]

		-The literature suggests this is one of the best clinical signs for indicating hypoxemia[a]
Stiff neck	Explanatory	-Danger sign indicative of severe malaria or other severe febrile disease[b]
Bulging fontanelle	Explanatory	-Danger sign indicative of meningitis[e]
The 15 2-way combinations between *Difficulty feeding, Very high respiratory rate, Central cyanosis, Chest indrawing, Grunting, and Lack of alertness*	Explanatory	-These symptoms are all indicators of illness severity -It is likely that HCWs might base care decisions on combinations of symptoms rather than based on just one symptom

[i] The Paediatric Admission Record (PAR) is an admissions form used to record medical information; it was implemented to improve recording of this information and to prompt recommended behaviour[Gachau et.al.2017]; a: Basnet et.al.(2006); b: WHO(2014a); c: Kenyan Ministry of Health(2016); d: Zhang et.al.(2011); e: WHO(2013); f: Wandeler et.al.(2015)

ii) Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?

In this regression model, I included the same variables as in the full model of regression 1, with the addition of *Oxygen use*, the diagnoses variables (because HCWs might follow guidelines on oxygen provision for particular diagnoses) and *Antimalarials* (controlled for as a marker of severity).

iii) Are children who obtain pulse oximeter readings below 90% more likely to obtain oxygen therapy than children with similar characteristics who obtain pulse oximeter readings of 90% or higher?

Instead of starting with a full model and then developing a reduced 'best-model' for Research Question 3, I used the best-model of Research Question 2, but replaced *Pulse oximeter use* with *Pulse oximeter value*. I did this because, in Research Question 3, I wanted to control for everything other than pulse oximeter use that influences oxygen provision, to determine how

HCWs' decisions on oxygen use are impacted specifically by whether the pulse oximeter value is high vs. low.

Table 3.5: Variables included in each regression's full model

Variable	**Regression 1 (with whom are pulse oximeters used)**	**Regression 2 (does pulse oximeter use affect oxygen provision)**
Pulse oximeter use		
Pulse oximeter value		
Oxygen use		
Weekend admission		
Admission time period		
Hospital		
Hospital use of pulse oximeters by admission month		
Sex		
Age in years		
Weight-for-age		
Paediatric Admission Record (PAR) use		
Length of illness before admission		
Fever		
Cough		
Difficulty breathing		
Vomit everything		
Difficulty feeding		
Convulsions		
Very high respiratory rate		
Oedema		
Stridor		
Central cyanosis		
Chest indrawing		
Grunting		
Wheeze		
Crackles		
Capillary refill		
Pallor		
Lack of alertness		
Difficulty drinking		

Stiff neck		
Bulging fontanelle		
The 15 2-way combinations between *Difficulty feeding, Very high respiratory rate, Central cyanosis, Chest indrawing, Grunting, and Lack of alertness*		If significant in R1
Diagnosis pneumonia		
Diagnosis malaria		
Diagnosis TB		
Diagnosis diarrhoea		
Diagnosis dehydration		
Diagnosis malnutrition		
Diagnosis anaemia		
Diagnosis meningitis		
Diagnosis asthma		
Diagnosis bronchiolitis		
Diagnosis sepsis		
Antimalarials		

Note: shading indicates that the variable was included

3.11.4 Regression outputs

I obtained the coefficients for each variable from the regressions, along with their associated p-values and confidence intervals, and from this, calculated odds ratios and 95% confidence intervals.

3.11.5 Developing a best-fit model

For Research Question 1 and 2, I used two methods to develop two reduced models for each Research Question, as a form of sensitivity analysis to help justify why the final best-fit model was chosen.

i) Reduced Model A

I manually derived Reduced Model A by using backwards stepwise regression.

The process for backwards step-wise regression was as follows: I first removed the non-statistically significant variable ($p \geq 0.05$) with the smallest coefficient from the model (as long as this variable was not one that I was controlling for) and then checked the coefficients and p-values produced by running a regression with the model without this variable. If the coefficients and p-values of the variables left in the model did not change much, I left that variable out and then removed the non-statistically significant variable with the next smallest coefficient. I continued this process, removing one variable at a time and checking the consequences, until the only variables left in the model were those I was controlling for, those with a p-value less than 0.05 and those which when removed, led to a substantial change in the model's outputs. ('Substantial change' was a subjective measure; with each iteration of the regression, a coefficient of 0.184 may change to e.g. 0.189 without causing concern, but if after a variable was removed it changed to e.g. 0.350, and various other variables underwent similar changes, this would be judged to constitute substantial change and the variable would be put back in the model). I did not remove any interaction terms until both of the individual component variables of the interaction term had been removed.

i) Reduced Model B

I carried out the following steps first for Research Question 1 and then for Research Question 2, to produce a Reduced Model B for each Research Question:

- I randomly selected 3 out of the 30 imputed datasets that had been created when multiple imputation was carried out with the original dataset
- I used bootstrapping to create 30 datasets from each of these 3 imputed datasets
- I carried out stepwise selection using Akaike information criterion (AIC) [Chaurasia&Harel,2012] on each of the 3 collections of 30 datasets; this thus produced 30x3=90 reduced models

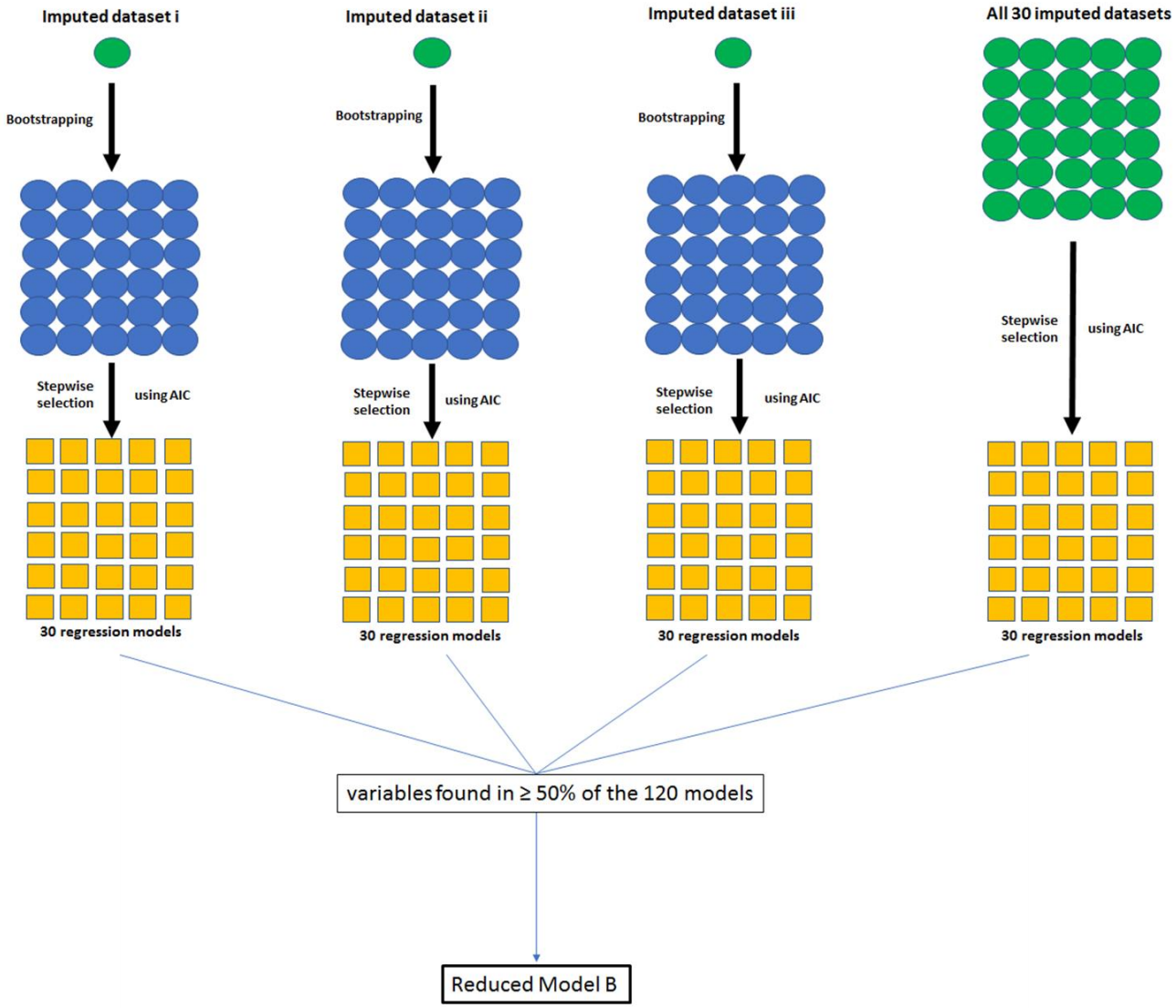
- Independently from the above steps, I ran stepwise selection using AIC for each of the 30 imputed datasets originally created from the original dataset through multiple imputation; this thus produced 30 reduced models
- Finally, I selected the variables that were found in 50% or more of these 120 AIC models, and included these variables to create Reduced Model B

Figure 3.4 shows this process.

I used bootstrap AIC for creating Reduced Model B in order to produce a more stable model than by using manual backwards stepwise regression; in the literature, it has been argued that bootstrapping is a good way to do this. This is because, in running the AIC process on multiple bootstrapped-derived datasets, and only choosing variables for the final model that are present in a defined proportion of the produced models (in this case 50%), I can take into account the variation in the data, and reduce the chance that unimportant 'noise' variables will be randomly selected or that important variables will be missed out by chance, which can otherwise occur when simply conducting stepwise selection once.[Heymans et.al.2007; Wood et.al.2008; Austin&Tu,2004; Vergouw et.al.2010]

Finally, I compared Reduced Model A and Reduced Model B descriptively to decide which was the best-fit model, based on topic knowledge, and the odds ratios and confidence intervals produced by each model (see Sections 5.5.1 and 5.6.1).

Figure 3.4: The process that was used to produce Reduced Model B (described in detail above)



Reduced Model B was therefore composed of variables found in the majority of the 120 models produced through stepwise selection using AIC on i) 3x30 models produced through bootstrapping of 3 randomly chosen multiply imputed datasets, and ii) all 30 datasets originally produced through multiple imputation

3.11.6 Pneumonia analyses: Are the results for Research Questions 1-3 different for children who have vs. do not have pneumonia?

I wanted to also separately analyse the children with pneumonia because pneumonia is the most common diagnosis of children presenting to these hospitals, [Ayieko et.al.2016] hypoxemia is particularly common in children with pneumonia [Lozano,2001], and pneumonia is the leading

cause of death worldwide in children of the age range examined in this study [Liu et.al.2016], so care of hypoxic children with pneumonia is particularly crucial.

To do so, I used *Diagnosis pneumonia* to divide each of the three Research Question datasets into two: the children with pneumonia and the children without. I then carried out the same steps as with Research Questions 1, 2 and 3, for producing full models, Reduced Models A and B, and deciding on the best-fit model.

I then examined the differences between the best-fit model of the children with vs. without pneumonia, e.g. which variables were found in one best-fit model but not the other, and the similarities and differences in the relative influence of variables found in both.

3.11.7 Assumptions

In running these regressions, we make the following assumptions [Stoltzfus,2011; Statistics Solutions]:

i) The outcome variable is dichotomous

Pulse oximeter use and *Oxygen use* are both dichotomous.

ii) The outcome variable should be coded with values of 1 and 0; values of 1 should be the outcome of interest

The outcome variables were coded thus.

iii) All influential variables should be included in the model (no under-fitting) but no non-influential variables should be included in the model (no over-fitting)

We ensured that no under-fitting occurred by including in the full model a large range of variables that were felt, because of background knowledge, the descriptive analyses, and/or the

previous regression's results, to be likely to influence the outcome of interest. We ensured that no over-fitting occurred by carrying out the backwards step-wise regression to develop a reduced 'best model'.

iv) The observations should be independent, i.e. there should not be multiple measurements from the same people

Observations were only recorded once per admission.

v) There should not be multicollinearity between the explanatory variables

The issue of multicollinearity was examined by first calculating the Generalized Variable Inflation Factor (GVIF), using the 'car' package in R [Fox et.al.2017], for each variable for each full regression model (before the regression models were run) (This coding can be seen in Appendix 3.9).

There is no consensus on which threshold to use to decide which GVIF values suggest multicollinearity. The San Diego State University Statistical Consulting Group states that variables with a GVIF above five should be removed; Paul Allison at the University of Pennsylvania claims that a GVIF>2.5 suggests potential multicollinearity, but that if this variable is a control variable, actions do not need to be taken; and Penn State Eberly College of Science advises researchers to further examine variables with a GVIF of four, and that GVIFs of 10 or more indicate severe multicollinearity that needs attention.

R produces an error message if it detects very strong multicollinearity when GVIFs are calculated; if this occurred during my analyses then I would remove the problematic variable. If no error message was produced, then, based on the literature, if a value of >2.5 was found, I would further assess this variable's potential multicollinearity by exploring its relationship with other variables with which it may have a multicollinear relationship. If potential multicollinearity was found with a control variable, the variable would be kept in the regression; however, if an

explanatory variable was found to invalidate the multicollinearity assumption, then its removal would be considered.

vi) The explanatory variables should be linearly related to the log odds

This was assumed to be the case.

vii) There should not be strongly influential outliers

I did not find any strongly influential outliers in the descriptive analyses stage.

vii) A large sample size is needed

27,914 children were included in the analyses, 17,107 of whom had at least one missing value.

Chapter 4: Methods and analysis plan for qualitative interview analyses

4.1 Pulse oximeter use in low-income settings

Little research in any setting has examined why pulse oximeters are not used even when available. The limited literature suggests that often, healthcare workers (HCWs) have inadequate knowledge on pulse oximetry and the interpretation of the measurement; they do not realise pulse oximeters' usefulness for diagnosing and treating children; and barriers to using pulse oximeters in clinical practice include insufficient availability and repair issues. These factors are described below within Berwick's framework (see Section 1.2.2).

i) Perceptions of the technology: Awareness of the utility of using pulse oximeters in clinical practice

When Ginsburg et.al.(2012) conducted a survey of 97 clinicians in 19 countries in Africa, Asia and South America, they found that many participants did not value pulse oximeters for their recommended roles: only 65% and 42% thought that pulse oximeters are extremely important for patient care and childhood pneumonia, respectively, while only 19% strongly agreed that pulse oximeters are very useful for diagnosing pneumonia. In a separate study, Ginsburg et.al.(2014) surveyed 81 Cambodian clinicians about pulse oximetry and barriers: only half of participants thought that pulse oximetry is very important for patient care and/or childhood pneumonia.

ii) Characteristics of those who do or do not use the technology: Knowledge

A systematic literature review of 14 studies examining HCW knowledge concerning pulse oximeters in Nigeria, Turkey, and 5 high-income countries found that, even when pulse oximeters were regularly used, HCWs, including senior clinicians, often had a large gap in

knowledge.[Elliott et.al.2006] Chohedri&Dahghani(2006) found similar results in Iran. In Orimadegun et.al.(2011)'s survey of 157 paediatricians and 224 in-training paediatricians across Nigeria, 4%, 29%, and 18% of participants answered all questions correctly about pulse oximeter accuracy, indications, and results interpretation, respectively; 73% thought more training on pulse oximetry was necessary.

iii) Factors relating to the context where the technology has been implemented: Organisational constraints

The most common pulse oximetry barriers participants in Ginsburg et.al.(2012)'s global survey identified were insufficient guidelines or policies (54% identified), inadequate supply (53%), competition for use by other services (53%), insufficient training (46%), and perceived costliness (35%); also 48% of participants said there were broken pulse oximeters at their facility. In Ginsburg et.al.(2014), 95% of Cambodian participants said they had received insufficient training on pulse oximeters, while 90% complained of insufficient guidelines or policies, and 50-65% thought that repairs, missing parts, use by others, inadequate reliability, and/or insufficient supply were barriers to pulse oximetry. 90% said they would use pulse oximeters most or all of the time if there were no barriers. Various studies mention that problems with repairs and spare parts of pulse oximeters and other oxygen equipment can often be an issue in low-income settings, but generally very few specifics are given.[Duke et.al.2008; Weber&Mulholland,1998; Hodges et.al.2007; Thoms et.al.2007; Duke et.al.2009; Malkin&Keane,2010; Bradley et.al.2015; Crede et.al.2014]

4.2 Using qualitative interview research to understand the quantitative data analyses findings and explore barriers to pulse oximeter use

In exploring HCWs' opinions and experiences of pulse oximeters through this qualitative research, we can gain an in-depth, multi-faceted understanding of *why* HCWs perform the behaviours the quantitative research findings illustrate, while exploring barriers to pulse oximeter use.

This qualitative research was conducted within a sequential mixed-methods design (see Section 1.3.5). The qualitative data collection and analysis followed and was informed by the quantitative dataset analyses. The integration of the quantitative and qualitative findings are reported in the Discussion (Chapter 7). The topic guide, and data collection and analysis methods, were deliberately flexible to allow an exploration of contradictory views (including those refuting the Clinical Information Network (CIN) analyses results), and areas not covered by the quantitative dataset analyses, which only examine factors at the HCW/patient interface. See Section 3.3.5 for more details on this approach.

As the qualitative research findings are of a snapshot in time and followed the CIN data analyses, the findings help elucidate the general perceptions, behaviours and barriers associated with pulse oximetry in Kenyan hospitals, rather than explaining factors specific to the time period covered by the quantitative data (September 2013-February 2016). The qualitative findings might also capture information on changes occurring after the admissions data were collected.

4.3 Research Questions

1. Why might HCWs choose to use or not use pulse oximeters?

2. Why might HCWs not be able to use pulse oximeters even if they want to?

3. When pulse oximeters are used, how are they used? Are guidelines/recommendations followed?

I investigated these Questions using a combination of direct observations, semi-structured interviews, and less formal discussions, each of which is described below.

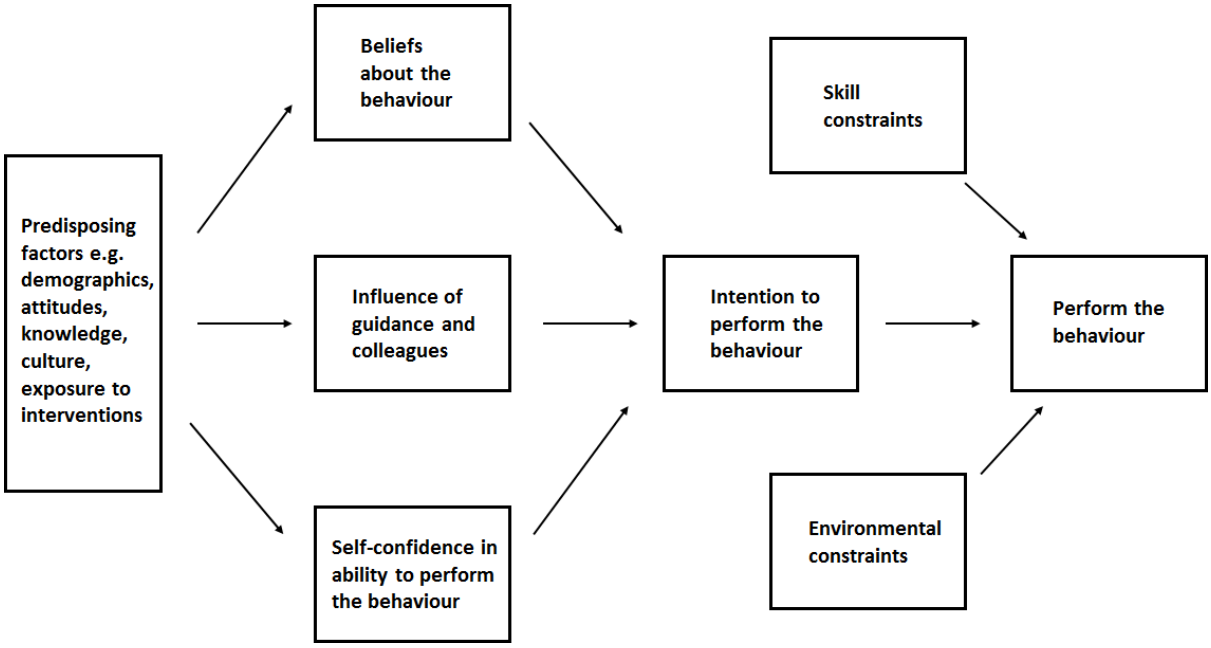
4.4 Theoretical frameworks

I utilised theoretical models and frameworks throughout this qualitative research. While formulating the Research Questions and methods plan I consulted a range of theories and frameworks on health technology diffusion and/or uptake, most notably theories developed by Rogers, Greenhalgh et.al., Normalisation Process Theory, the Theoretical Domains Framework, the Behaviour Change Wheel, and the Consolidated Framework for Implementation Research (CFIR), each of which I discuss in more detail in Section 1.2.2. I found that, of these, the CFIR was nuanced, expansive, logical, and clear, and was relevant to the research topic, so I referred to this framework while developing my interview topic guide questions (see Section 4.6). The 'intervention characteristics' domain of this framework is highly related to Berwick's 'perceptions of the technology' construct (see Section 1.2.2), while the CFIR's 'characteristics of individuals' and 'inner setting' map closely to the 'characteristics of those who do or do not use the technology' and 'factors relating to the context where the technology was implemented' constructs, respectively.[Berwick,2003] The CFIR has added complexity in placing further emphasis on the broader 'external setting' by highlighting this with its own domain, and in emphasising the importance of the implementation process, as the fifth domain.

I used an iterative approach to coding the data and applying a framework to organise the findings. I aimed to identify the concepts, categories and themes from the data rather than impose a pre-determined theory or framework. I initially coded the interview data (described in Section 4.10) without theories/frameworks. As the process progressed I organised the findings within the CFIR and found that this framework was not appropriate for the findings: several of the framework's constructs were not relevant, e.g. the technology's adaptability and trialability, the hospital's structural characteristics (age, maturity, size etc.), how the individuals (HCWs) identify with the hospital, the role of "formally appointed internal implementation leaders". Moreover, several themes emerged from the qualitative research that the CFIR does not include, e.g. technology characteristics such as reliability; organisation supply and maintenance structures and processes; and the distinction between HCWs' intention to use a pulse oximeter vs. their ability to do so.

I therefore considered further theories, and decided that the best organising framework for my data was the Integrative Model of Behavioural Prediction (IMBP). This model contends that whether someone performs a behaviour depends on two factors: whether the person intends to perform it, and whether they can do so.[Fishbein&Yzer,2003; Fishbein&Ajzen,2010] The elements that influence these factors are illustrated in a causal flow diagram (Figure 4.1).

Figure 4.1: The Integrative Model of Behavioural Prediction, adapted from Fishbein&Yzer(2003) and Fishbein&Ajzen(2010)



This framework is particularly relevant to the interview data as it provides a logical progression from beliefs about a behaviour (pulse oximeter use), to a decision to perform the behaviour (e.g. the intention to do so), to actually performing the behaviour, dependent on the individual having the appropriate skills, and there not being any environmental constraints (i.e. factors external to the individual, e.g. technology characteristics, other individuals' actions, organisational policies and practices). While in reality this progression is not perfectly linear, and the components are interconnected, the data suggest that HCWs' pulse oximeter use roughly follows this pathway. Thus, for HCWs to use a pulse oximeter, they first need to want to use one, and then they need to be able to do so (i.e. they must have the knowledge and skills to use pulse oximeters, and there must not be barriers preventing them from doing so). The IMBP is also a good fit for my findings because all the constructs, (Figure 4.1), are relevant to the data (see Chapter 6). Moreover, the IMBP considers factors affecting the HCW-patient interaction while also considering influences at the interpersonal (e.g. between colleagues) and environmental (e.g. externally imposed from the organisation and beyond) levels, which are important in this context where international, national, county, hospital, departmental and individual-level

factors may influence HCW behaviour (See Appendix 3.2 for potential factors operating at different health system hierarchy levels).

The constructs of Berwick's model are also included within the IMBP: 'perceptions of the technology' is found within the IMBP's 'beliefs about the behaviour' and 'influence of guidance and colleagues'; 'characteristics of those who do or do not use the technology' is found in the IMBP's 'predisposing factors', 'beliefs about the behaviour' (e.g. HCWs' attitudes) and in the skills constraints (e.g. HCW knowledge); and 'factors relating to the context where the technology has been implemented' is encompassed within the IMBP's 'skill constraints' and 'environmental constraints'. However, while Berwick's three themes are broad, the IMBP enables a more granular analytical approach where more specific factors can be considered, as can their placement along HCWs' decision-making and behaviour-performing pathway.

4.5 Study design

I carried out direct observations in three hospitals and conducted 16 semi-structured interviews with HCWs from four hospitals. I also engaged in less formal discussions with 14 HCWs and hospital staff from 12 hospitals that covered similar topics as the semi-structured interviews, which I will hereafter refer to as semi-structured conversations.

I used a mixture of deductive and inductive approaches. In an inductive approach, explanations and theories are drawn from data while in deductive approaches, theories and hypotheses are established first, then data are collected and analysed to confirm or disprove the hypotheses.[Bernard,2011] The topic guide's content and structure were deductively informed by the systematic review and dataset analyses findings (see Chapters 2 and 5). I used inductive approaches to reflect on interview findings and continuously revise the topic guide for

subsequent interviews, and to explore new ideas during coding, drawing themes from the data, not from pre-determined hypotheses.

4.6 Approaches

The observations' aim was to better understand how each hospital is organised and functions; their admissions processes; their physical environment (e.g. number of rooms and beds) and equipment availability; HCWs' general behaviour; and when/how pulse oximeters are used, particularly during the admission process. These observations then helped with creating the interview topic guide.

During semi-structured interviews, a topic guide is loosely, not prescriptively, followed; the questions asked depend on the participant's responses. I specifically conducted semi-structured interviews because I wanted to have enough structure to explore topics I knew I wanted to investigate (based on the literature, the dataset analyses, and key informant conversations), while having the flexibility to explore other areas participants raised (as I recognized there would likely be important factors I had not predicted), and for the discussed topics to evolve based on previous interviews.

I designed topic guide questions to be open-ended, to discourage one-worded answers; non-leading, i.e. allowed participants to suggest ideas rather than presenting ideas to them; and non-judgemental, i.e. did not make value judgments on decisions not to use pulse oximeters. I also wanted to capture influential factors operating at different health system hierarchy levels (factors affecting the HCW-patient interaction, those at the departmental and county levels, etc.; see Section 3.3.1) and so ensured question topics spanned these levels. The CFIR informed this (see Section 4.4). Once I developed a draft topic guide, I discussed the questions' relevance and wording with key informants, including several Kenyans at the KEMRI-Wellcome Trust

Research Programme (KWTRP) with clinical and/or research experience in Kenyan hospitals, and other researchers and paediatricians with experience in these hospitals. As the interviews progressed, I adapted the topic guide based on participants' responses. For example, early on it became apparent that many HCWs found the issue of pulse oximeter reliability important; I therefore asked the remaining participants about this. (Appendix 4.1 and 4.2 contain the topic guide as it was before interviews were conducted, and at the time of the last interview, respectively)

'Semi-structured conversations' refers to one-on-one discussions with HCWs and other hospital staff; compared with the semi-structured interviews, these were shorter (5-15 minutes vs. 20-35) and less formal. These conversations supported, countered, and further explored ideas discussed in the semi-structured interviews.

4.7 Participants and setting

4.7.1 Participants

I conducted semi-structured interviews with paediatricians, Medical Officers (MOs), Medical Officer Interns (MOIs), Clinical Officers (COs), Clinical Officer Interns (COIs), and nurses. COs are non-physician clinicians, who undergo a three-year medical diploma course and one-year internship; they are more restricted in their practice than physician clinicians, but can be involved with many care aspects e.g. diagnosing and treating, and can specialise in e.g. paediatrics, anaesthesia, dermatology, carry out minor surgery, and run health centres. MOs are physician clinicians, who have not undergone postgraduate training to become consultants in, e.g. paediatrics. HCWs in each of these roles are expected to use pulse oximeters, although the MOs/MOIs and COs/COIs are most likely to conduct the initial admissions assessment.[Mbindyo

et.al.2013; Mullan&Frehywot,2007; English et.al.2004] Based on advice from key informants involved in conducting interviews with Kenyan hospital HCWs, I aimed for 16-25 interviews; this number of interviews has been shown to be sufficient to obtain saturation.[Hennink et.al.2016] In total, I conducted 16 interviews, with one paediatrician, five MOs/MOIs, four COs/COIs, and six nurses.

I conducted 14 semi-structured conversations. This included four paediatricians, three MOs and four nurses, from ten CIN hospitals, whom I talked with at a two-day meeting unrelated to this research. At this meeting, paediatricians, MOs, nurses and data officers from 14 CIN hospitals discussed care and medical data recording assessments and recommendations. The topic guide themes were discussed in these conversations, but in a shorter, less formal, less detailed manner. It was not practical to conduct semi-structured interviews with these HCWs because of their time limitations. Furthermore, the semi-structured conversation format was an advantage in this context as, through speaking to more HCWs and doing so outside of the ward, I obtained a greater diversity of information, experiences, and opinions on the research topics; also, in having a more informal format, participants were likely to be more willing to bring up controversial topics than during interviews. Moreover, the conversations were conducted with HCWs from the ten CIN hospitals where I did not conduct interviews, so I was able to obtain additional perspectives, and better understand differences/similarities in experiences across hospitals.

I also conducted conversations with two Procurement Officials and one Medical Superintendent from two hospitals where I conducted semi-structured interviews. In these conversations, we explored the equipment procurement process, a narrower topic than explored with the HCWs and hence the shorter format was appropriate.

4.7.2 Setting

The observations were conducted in CIN hospitals, and the interviews and conversations were conducted with hospital staff from CIN hospitals. The CIN hospitals are public (district) hospitals that are first referral centres. (Section 3.3.4 describes the CIN; Table 4.1 provides characteristics of the hospitals in which observations were conducted, and the interview and conversation participants work.)

I carried out the direct observations in the admitting areas and paediatric wards of three CIN hospitals, selected for convenience, and to identify a range of pulse oximeter use levels. Observations were conducted on weekday mornings.

I conducted the interviews in four CIN hospitals (I had carried out the observations in two of these). I intended to conduct interviews in two hospitals where pulse oximeters are used widely, and two where pulse oximeters are used rarely if at all, based on the quantitative research descriptive findings (see Appendix 5.2). However, the two hospitals selected for their minimal pulse oximeter use obtained pulse oximeters after the quantitative data were collected and therefore HCWs were using pulse oximeters in these locations; an effect sometimes termed 'the diffusion of treatments'.[Bernard,2011] I could nonetheless still explore situations when pulse oximeters are not used, as most HCWs from the four hospitals had experience of this due to widespread barriers to use; furthermore, I could compare whether pulse oximeter views and experiences differed for HCWs in hospitals where pulse oximeters had been introduced recently vs. earlier.

The three conversations conducted with a Medical Superintendent and Procurement Officials were conducted in the participants' hospital offices.

Table 4.1: Characteristics of the CIN hospitals where qualitative research took place

Characteristics	Direct observations	Semi-structured interviews	Semi-structured conversations with HCWS at CIN meeting	Semi-structured conversations with Medical Superintendent and Procurement Officials
Number of hospitals	3	4	10	2
IDs of hospitals	#5, #6, #12	#5, #7, #11, #12	#1, #2, #3, #4, #6, #8, #9, #10, #13, #14	#5, #12
Number of counties	2	4	10	2
Paediatric ward capacities (# beds)	35-42	30-60	21-63	35-42
Paediatric admissions per year	1,500-2,300	1,500-3,500	1,300-4,100	1,500-2,300
% of catchment area populations living in extreme poverty	20-55%	20-55%	20-65%	20-55%
% of children obtaining pulse oximeter reading on average between Sept 2013 and Feb 2016	0-75%	0-75%	0-52%	0-75%

[Ayieko et.al.2016]

4.8 Recruitment and data collection

Observations

Observations took place over several hours in each of the three hospitals. This consisted of speaking with hospital staff (one of whom introduced the hospital and its admissions process), and observing HCWs' behaviours. Most notes were taken afterwards, to reduce interruption and limit HCW discomfort from my presence.

Semi-structured interviews

I used a combination of purposive and snowball sampling to recruit the semi-structured interview participants, based on convenience and hospital staff preference. When I first arrived, generally a HCW showed me around and introduced me to other HCWs; I interviewed this HCW if they consented. Recruitment of others was through: a) directly approaching those who did not seem busy then; b) snowballing: participants identifying others; c) the paediatrician and/or head nurse identifying potential participants. Whichever method, those recruited were always HCWs directly involved with patient assessment on a typical day.

I aimed to obtain varied views i.e. from nurses, COs/COIs, MOs/MOIs and paediatricians. Participants simply needed to be HCWs (as all HCWs were expected to use pulse oximeters); there were no exclusion criteria. I could therefore be flexible in recruitment, which was helpful because the wards were very busy so at any one time, there were few HCWs available for interviews. Appendix 4.3 contains a list of the main recruitment difficulties and Section 7.3.3 describes the limitations. The most common reason HCWs declined to participate was being too busy, while a few simply did not want to participate. HCWs of particular roles were no more likely to decline than others, and the reasons were similar across roles. Most HCWs were willing to be interviewed, if available. In recruiting participants, I said I was investigating how HCWs in Kenyan paediatric wards determine diagnosis and illness severity, rather than explicitly stating that I was interested in pulse oximetry. This was to see how, if at all, HCWs would bring up pulse oximeters unprompted, which would provide insight into their perception of pulse oximetry's importance and usefulness.

I conducted each interview in English as all participants were fluent in English. The participant chose the interview location. These ranged from nurse break rooms to consultation areas, admission areas/offices, empty meeting rooms, and empty ward rooms. Interviews lasted 20-35 minutes (not including introduction or consent (see Section 4.9)). Interviews were audio-recorded on two electronic recorders (to ensure no responses were lost/misremembered), if the participant consented to recording. One participant did not consent to recording, so I wrote notes instead.

I loosely followed the topic guide, to investigate when participants use pulse oximeters and why, their opinions of pulse oximeters, and barriers to their use. I was however steered by the participant's responses in deciding which topic guide questions to focus on during the interview, and in exploring other topics they raised and found relevant.

I was interested in pulse oximetry specifically at admission. However, if participants wanted to discuss other care stages, e.g. its use for monitoring or weaning off oxygen, I did not steer away from this, because it is valuable to holistically understand pulse oximeters' role in the whole care process, and the barriers at different care stages.

Semi-structured conversations

I used purposive sampling for the semi-structured conversations: I approached paediatricians, MOs and nurses at the meeting, generally directly, but was sometimes introduced by other meeting participants; I targeted HCWs from as large a range of hospitals as possible. Some asked to talk later but no one declined to participate. I directly approached one of the Procurement Officials and the Medical Superintendent in their hospitals; the other Procurement Official was approached by the Medical Superintendent.

Conversations at the meeting were conducted in quiet, semi-private areas the participant suggested or agreed upon. Conversations with the Procurement Officials and Medical

Superintendent were conducted in their offices. I took limited notes during the conversations (of e.g. quotes, general points, my reflections), and then wrote these in more detail immediately after.

4.9 Ethics

Before the hospital visits for the observations, I obtained permission from the Medical Superintendent and paediatrician at each hospital. When I entered the paediatric wards, I was shown around by a HCW from whom permission was sought to carry out the observations at that time. Hospitals and dates were kept anonymous in the documentation. I did not collect data on identifying information about HCWs or children, e.g. names.

I obtained ethical approval for conducting the semi-structured interviews from Oxford University's OXTREC ethical committee and from the local ethical committee in Kenya: the Kenya Medical Research Institute's (KEMRI's) Scientific and Ethics Review Unit (SERU). Appendix 4.4 contains approval confirmation letters. I also obtained approval from the Medical Superintendents of each hospital where I conducted interviews.

Before the interviews, I gave participants an Information Sheet explaining the research purposes; that their participation was voluntary and there would be no negative repercussions from participating, declining to participate or giving a particular response; and how their data would be confidentially stored (on a password-protected encrypted laptop) and used (only by individuals directly involved with this research). (Appendix 4.5 contains this sheet). Participants could keep this sheet for future reference. I discussed this information with the participant and asked if they had any questions. I then asked the participant to sign a Consent Form in duplicate to agree to being interviewed, for their responses to be used in this research, and for the interview to be audio-recorded. (Appendix 4.6 contains this form). I gave the participant one of

these signed Forms to keep and I kept the other one, in a secure location. The Information Sheet and Consent Form were created using templates specified by the KEMRI ethical committee. No incentives or compensation were provided to participants. Appendix 4.7 describes the main ethical factors associated with the interviews.

Informed consent was not deemed necessary for the semi-structured conversations as they were not audio-recorded and no identifying information, e.g. names or hospitals, was collected; the general ideas raised in these conversations are discussed in the results, rather than direct quotes, and these are anonymous so cannot be attributed to individuals. Furthermore, this research was not exploring a sensitive topic but rather an issue of common practice and service delivery.

4.10 Data management

I transcribed the interviews. Transcripts were kept anonymous by using codes to identify participants, and ensuring no identifiable information was included in the transcript.

The first analysis step was open coding: I described each phrase of each transcript with a concept label(s). I then consolidated these concepts in to a list, removing duplicates, and combining concepts to create categories. Then I further refined the categories to develop overarching themes. This process involved going back through the transcripts many times. Thus, the themes were extracted inductively from participants' experiences, beliefs, and what they thought is important, rather than being defined from theories/models, the literature, or the dataset analyses. I then went back through the semi-structured conversation notes to see whether these data supported the concepts, categories and themes identified from the interviews. I then selected quotes and ideas relevant for each concept/category/theme from the

interviews and conversations; quotes were chosen based on relevance, expressiveness, and clarity.

Finally, I used the IMBP (chosen after interviews were conducted, as it was the best fit model for the data; see Section 4.4) as a framework to organise these findings. I discussed the data's themes within this framework's constructs, using quotes to illustrate, explain or expand on these points, and I interpreted these findings.

4.11 Validity, triangulation and feedback of findings

4.11.1 Internal validity

i) Saturation

Sixteen interviews were conducted to reach saturation – the point at which no new information was being obtained through conducting additional interviews.

ii) Triangulation

By exploring the research questions through three qualitative methods, I could triangulate the findings, because if similar results were found regardless of the methods, this would strengthen their plausibility. This was demonstrated prominently when conversations' notes supported the concepts, categories and themes extracted from the interviews. Discussions with supervisors and other researchers in Kenya also helped validate the findings. Moreover, after transcribing the interviews, as part of the interpretation process (the 'translation'), I created a summary of the 10-20 main points of each interview, and emailed each participant their summary, asking if they thought the analyses were accurate and appropriate, if they had anything to add, change or clarify, and if they had any questions (a process termed 'member checking'). In addition to

helping triangulate and validate the research findings, this also helped foster participant engagement and showed interviewees that their participation was useful and valued.

iii) Reflexivity

Conducting and analysing qualitative research is an inherently subjective process, and so my findings would have been influenced by my background and experiences, e.g. that I am not Kenyan (and so do not have first-hand experience of the Kenyan healthcare system), and do not have a clinical background, and by my knowledge of the quantitative findings. My views would also have changed over time as I became more familiar with the topic and setting (e.g. in being able to compare behaviours across HCWs). Throughout the process I therefore needed to keep aware of my perspective and how it might influence the research.[Symon&Cassell,2012; Berger,2013]

4.11.2 External validity

This qualitative research provides in-depth insight into participants' experiences and perspectives, but, as is the nature of qualitative research, it involved a small non-randomized, non-representative group; therefore, I cannot conclusively generalize these findings to the population or other groups from a statistical standpoint.

However, from these findings we can understand the general picture of circumstances and issues that the larger Kenyan HCW population may experience, given that I interviewed HCWs across many areas of the country (CIN hospitals are located in 12 counties around Kenya); also other Kenyan district hospitals may share many characteristics (e.g. Ministry of Health decisions concerning funding and staffing). Moreover, hospitals in other low-income settings may have similar characteristics as the CIN hospitals, e.g. due to resource constraints and staff shortages; it

is therefore likely that these findings may be relevant in other low-income settings. (Section 7.3.1 contains further discussion of applicability assessment.)

4.11.3 Findings feedback

I presented this research at two stages to KWTRP researchers, many of whom work on the CIN, and/or have experience as HCWs in Kenyan hospitals. I received feedback from these presentations on my approach and analyses, and incorporated these suggestions and critiques. A summary of the final results, analyses and conclusions will be given to the participants, the management of the involved hospitals, the KWTRP researchers, and this research's partners, including the University of Nairobi, the Kenya Paediatric Association, and the Kenyan Ministry of Health, ensuring no place or person can be identified.

Chapter 5: Results for quantitative analyses

5.1 Overview

As detailed in Chapter 3, I analysed data from the Clinical Information Network (CIN) for this research. Several other studies have used CIN data, including to describe the characteristics of children admitted to these hospitals and variations in their treatments and outcomes [Ayieko et.al.2016]; show that the CIN has been successful at increasing the quality of data recorded on hospital admissions [Tuti et.al.2016b]; and evaluate, using the Behaviour Change Wheel, which aspects of the CIN implementation process were likely to encourage uptake of recommended practices (aspects included e.g. clinical guideline use, environmental restructuring, incentivisation) [English et.al.2017a].

I analysed a dataset of 27,914 child admissions to seven CIN hospitals to investigate the following Research Questions:

1) Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

2) Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy[3] than children with similar characteristics who do not obtain pulse oximeter readings?

3) Are pulse oximeter readings below 90% associated with the prescription of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?

The 90% threshold was chosen because the World Health Organization (WHO) and the Kenyan Basic Paediatric Protocols, which are the national guidelines for hospital care in children, both

[3] By 'obtain oxygen therapy' I am referring to obtaining a prescription/order for oxygen

recommend that if a child's oxygen saturation is below 90%, oxygen should be given.[WHO,2014b; Kenyan MoH,2016]

Secondary question: Are the results for Research Questions 1-3 different for children who have vs. do not have pneumonia?

As described in Chapter 3, I first cleaned and organised the data, then examined the patterns of and reasons for the missing data; next I carried out multiple imputation to take the missing data into account; I used backwards stepwise regression and Akaike information criterion (AIC) analyses, on the multiple imputed datasets and bootstrapping-derived datasets, to select the variables to include in the logistic regression models; and finally, I ran the regression models separately with each imputed dataset and combined the results using Rubin's rules[Rubin,1987].

In this chapter I will report the results of the descriptive statistics then the missing data patterns, followed by the multiple imputation process and analyses, and finally the best model development for the logistic regressions, and their results.

5.2 Results: descriptive statistics

The main descriptive analyses findings of the admissions data from the seven CIN hospitals included in the analyses (see Section 3.5.2) are described below. The full set of descriptive statistics is presented in Appendix 5.1.

i) Hospitals

The seven hospitals included in the analysis were selected because they were the CIN hospitals that used pulse oximeters with at least 20% of children on average over the study period (to ensure that enough data on pulse oximeter use were available for the analyses). (Appendix 5.2

contains a table of the 14 CIN hospitals' average levels of pulse oximeter use over this time period.)

These public (district) hospitals are first referral centres, located in five different counties.[Ayieko et.al.2016] Further descriptive characteristics are shown in Table 5.1:

Table 5.1: Characteristics of the CIN hospitals from which admissions were analysed

	Hospital 1[i]	Hospital 2	Hospital 3	Hospital 4	Hospital 5	Hospital 6	Hospital 7
Paediatric ward capacities[ii]	63 beds	38 beds	29 beds	38 beds	42 beds	41 beds	32 beds
% of catchment area populations living in extreme poverty[ii]	41%	49%	45%	49%	21%	21%	31%
Number of admissions examined in the dataset	4,299	2,727	3,957	5,734	3,845	3,992	3,360
Median age of admitted children	1 year	1 year	2 years	2 years	1 year	1 year	1 year
Pneumonia diagnosis	56% (n=2428)	50% (n=1366)	25% (n=973)	37% (n=2134)	53% (n=2051)	56% (n=2243)	44% (n=1487)
Malaria diagnosis	12% (n=511)	1% (n=22)	62% (n=2447)	68% (n=3893)	13% (n=487)	11% (n=451)	1% (n=27)
% on average with whom pulse oximeters were used over study period	52%	21%	47%	42%	75%	44%	74%
% with pulse oximeter value <90%[iii]	11%	18%	5%	12%	9%	20%	11%

% prescribed oxygen[iv]	12%	6%	3%	6%	11%	12%	5%
Mortality rate	5%	2%	7%	7%	8%	10%	2%

[l] The numbering of these hospitals is the same as that used throughout this thesis e.g. in Figure 3.1 and Figure 5.3

[ii] The data for these two variables were obtained from Ayieko et.al.(2016)

[iii] Of those with whom a pulse oximeter was used, so values will be dependent on the conditions of the children admitted to the hospital, and on with which groups of children HCWs use pulse oximeters in that hospital

[iv] This is % of all admissions, not the % of those who obtained a pulse oximeter reading or % with oxygen saturation <90%

Further discussion of the by-hospital variation in values shown in Table 5.1 is found in the subsections below.

ii) Demographics

Over half of admitted children included in the analysis were aged one year or younger (median: 1 year, range: 1 month-12 years); most were underweight for their age (mean Z-score of -0.83, e.g. -0.83 standard deviations below the WHO reference population's mean; see Table 3.1); slightly more males than females were admitted; and most were ill for three days or less before coming to the hospital.

iii) Symptoms and clinical signs

Three quarters of admitted children had a fever, over half had a cough; the other most common symptoms/signs were difficulty breathing (34%), difficulty feeding (34%), and indrawing (32%). (See Figure 5.1)

The most common symptoms/signs for children with pneumonia were cough (84%), fever (81%), and indrawing (62%). A similar set of symptoms/signs was recorded for children without pneumonia, although with smaller frequencies: fever (69%), cough (35%), and difficulty feeding (32%). (See Figure 5.2) The frequency of fever in children without pneumonia is probably because infectious disease is still the predominant cause of admission in Kenya and fever is a

common symptom of many of these conditions; the frequency of cough in children without pneumonia, but the low occurrence (relative to children with pneumonia) of other respiratory symptoms/signs associated with illness severity, e.g. indrawing and grunting, indicates that respiratory conditions less severe than pneumonia, and respiratory manifestations of other diseases, are also common in this population.

Figure 5.1: Percent of admitted children with each symptom/sign

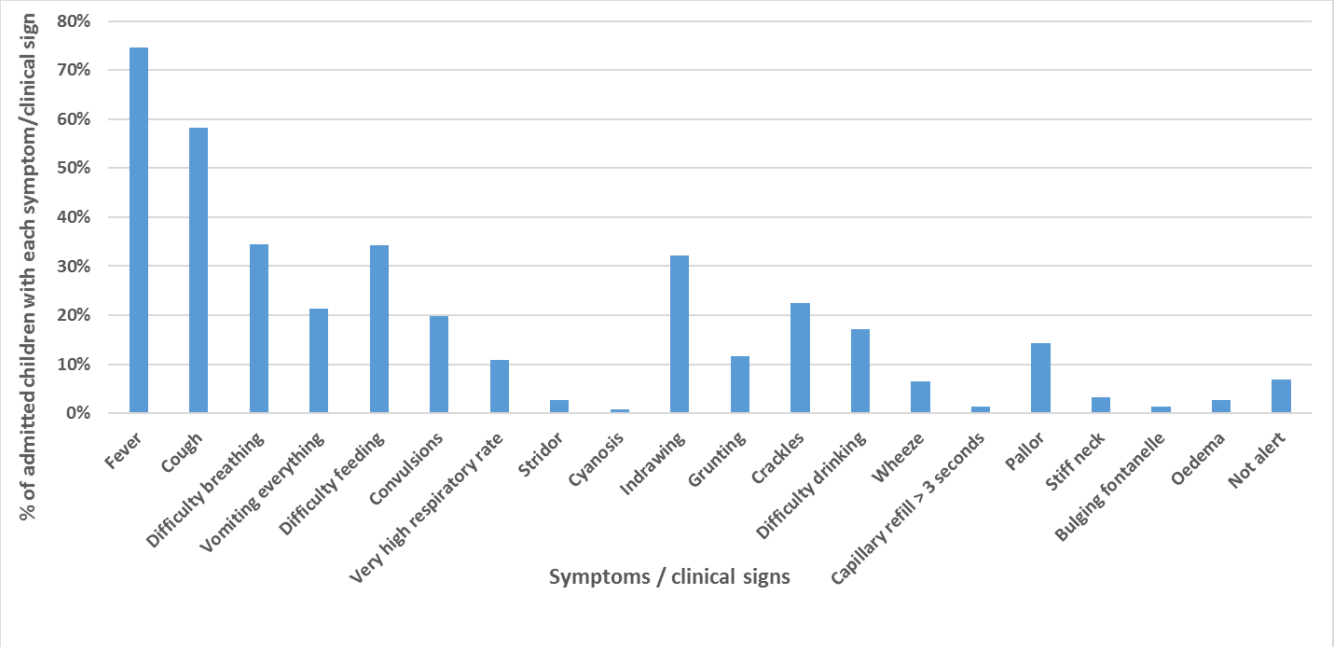
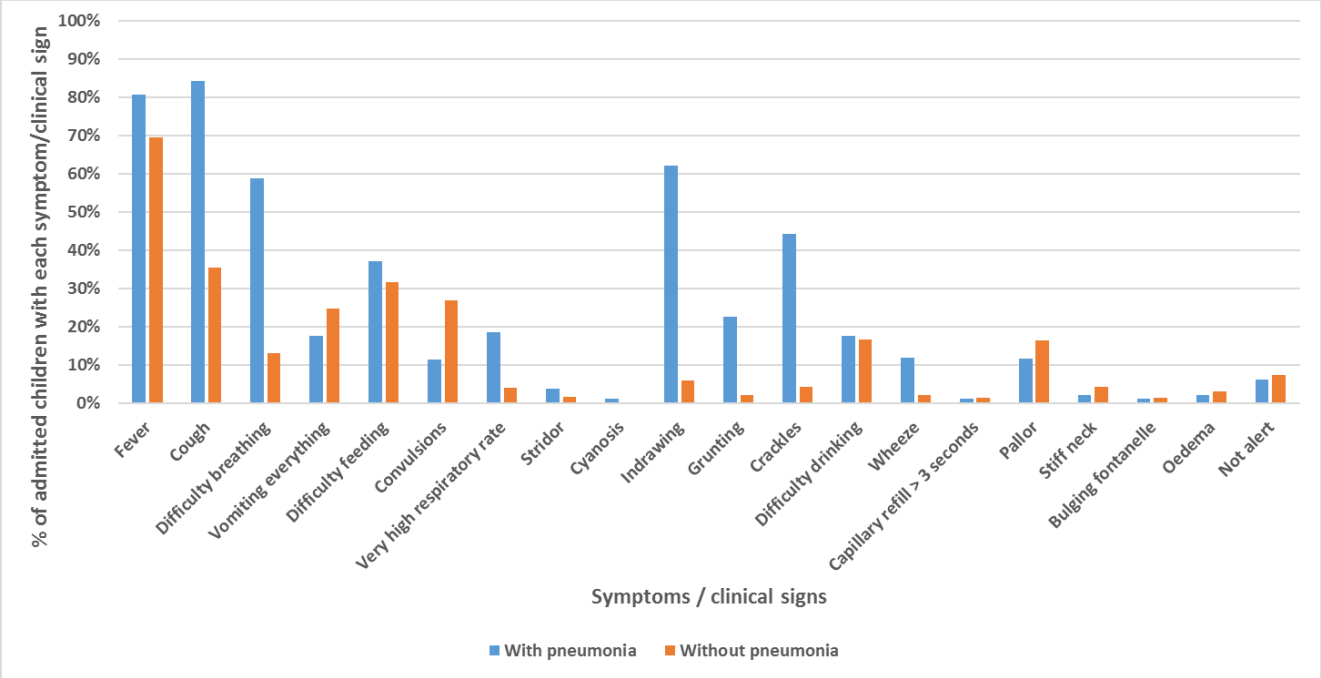


Figure 5.2: Percent of admitted children with and without pneumonia who had each symptom/sign



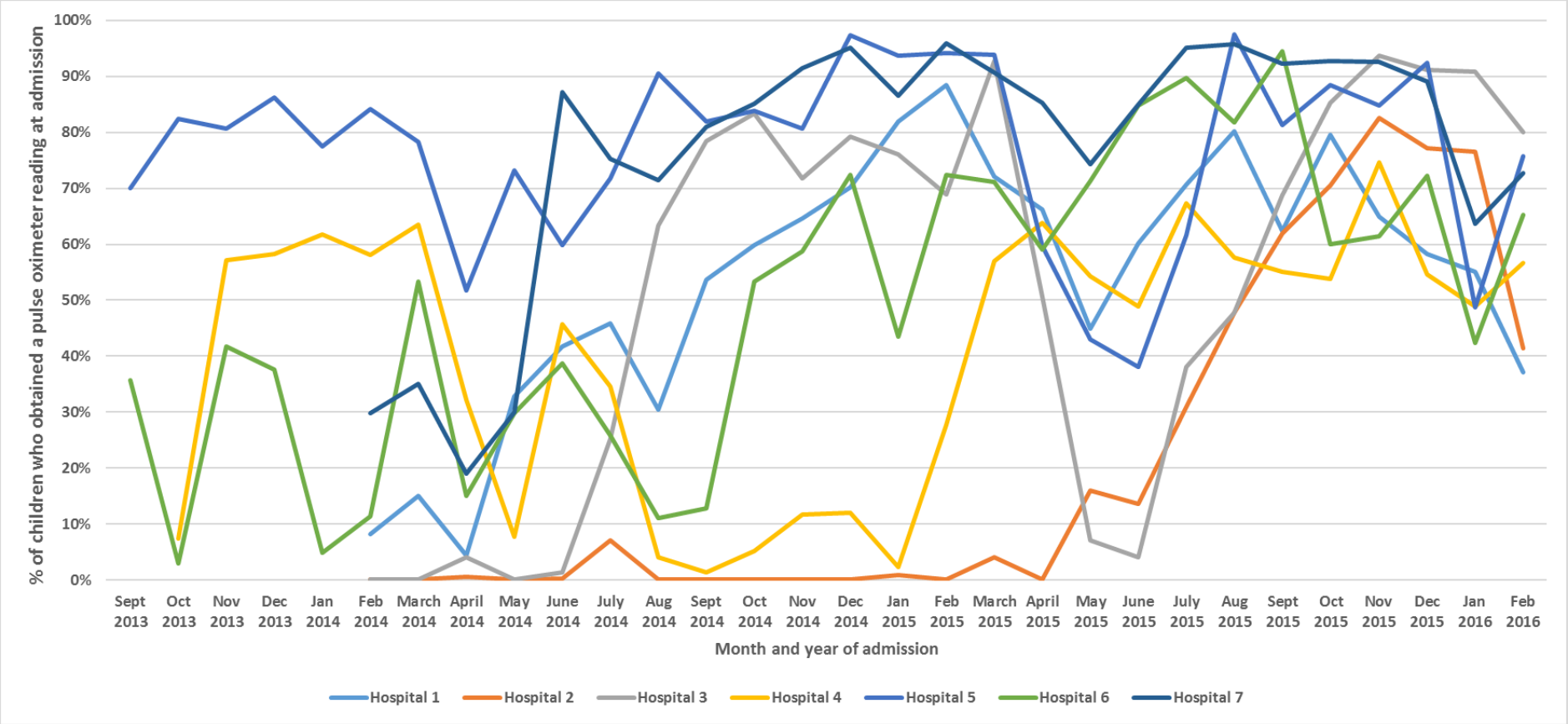
iv) Pulse oximetry

Roughly half of children in the seven CIN hospitals obtained a pulse oximeter reading, and of these, about 10% had an oxygen saturation level below 90%.

Pulse oximeter use varied greatly across hospitals, and within hospitals over time, but on average, pulse oximeter use increased over time. Figure 5.3 shows this. (Appendix 3.1 contains individual figures for each of the 14 CIN hospitals and Appendix 5.2 contains a table of each hospital's average level of pulse oximeter use over this time period.) Potential reasons for this pattern are explored in Chapters 6 and 7.

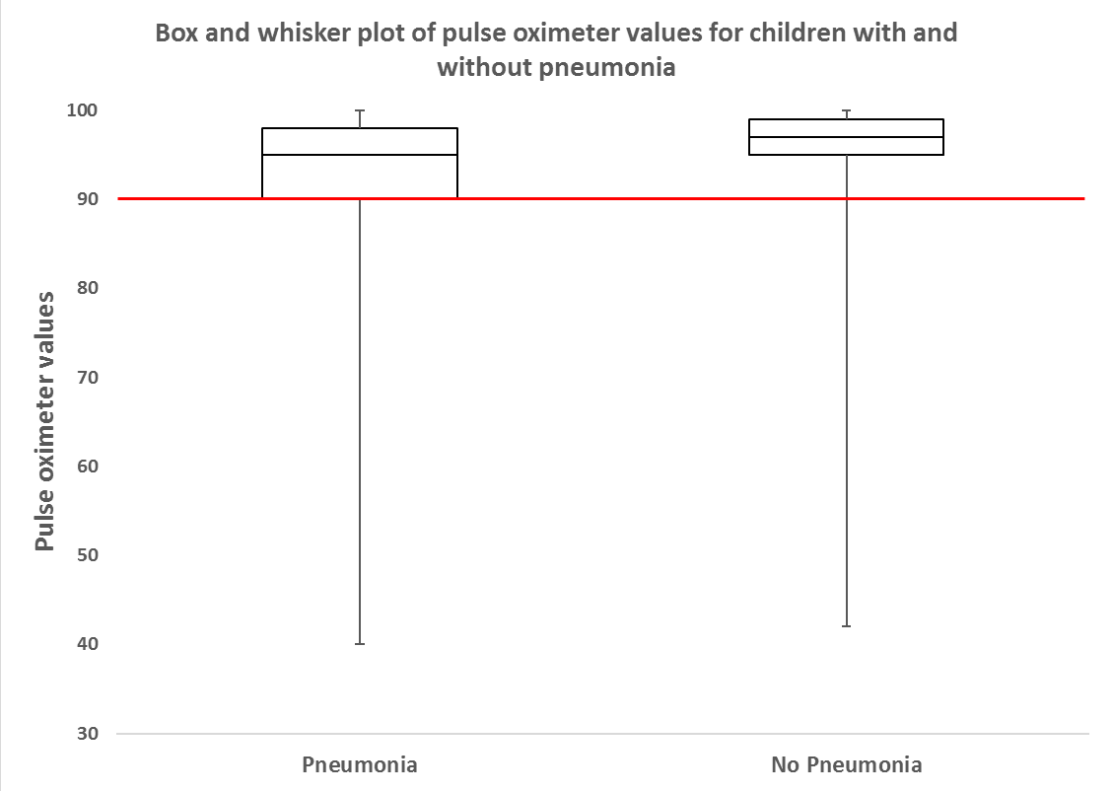
On average, 54% and 48% of children with and without pneumonia obtained a pulse oximeter reading, respectively, and of these, 19% and 4%, respectively, had an oxygen saturation level below 90%. (See Figure 5.4) Patterns of pulse oximeter use over time were very similar for children, regardless of whether they had pneumonia or not, as shown in Figure 5.5.

Figure 5.3: Pulse oximeter use from Sept 2013-Feb 3016 at each of the seven CIN hospitals included in the analyses



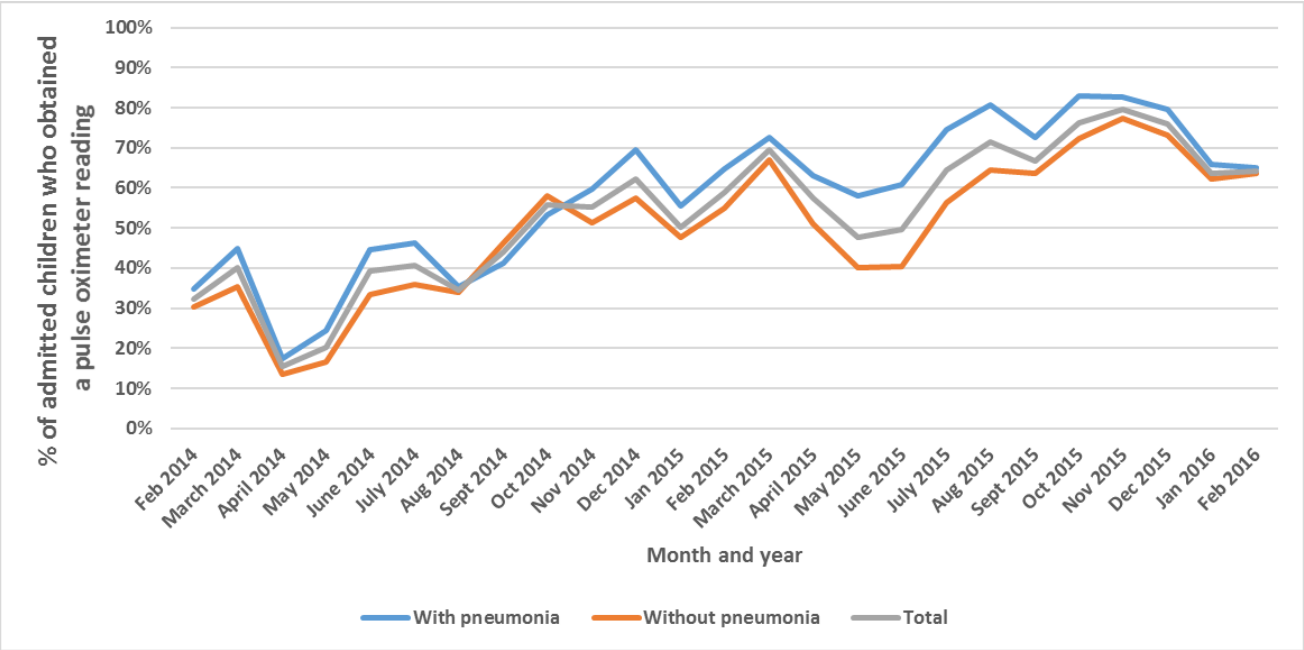
Note: hospitals entered in to the CIN at different months (all had entered by February 2014), so lines in Figure 5.3 begin at different dates.; See Appendix 3.1 for individual figures for each of the 14 CIN hospitals. Potential reasons for variability are described in Section 7.2.

Figure 5.4



Note: the red line indicates the 90% threshold below which guidelines recommend oxygen is given; the middle horizontal line of the box is the median pulse oximeter value, the upper and lower horizontal lines are the 25th and 75th percentile, and the vertical lines extend across the range.

Figure 5.5: Over time, the percent of all children (pooled across the seven CIN hospitals) and of those with and without pneumonia who obtained a pulse oximeter reading



Note: The figure begins in February 2014 because hospitals joined the CIN in different months, and all had joined by February 2014.

v) Diagnoses

The most common diagnoses were pneumonia, diarrhoea and malaria: 45%, 35%, and 28% of children, respectively, had these diagnoses. (See Figure 5.6)

The most common diagnoses of children who did not have pneumonia were diarrhoea (39%), malaria (37%), and dehydration (23%).

Children often had multiple diagnoses. For instance, of the children with pneumonia, 29% also had diarrhoea, 17% had malaria, and 16% had dehydration. (Figure 5.7 is a Venn diagram of pneumonia and malaria diagnoses)

As shown in Table 5.1 and Figure 5.8, diagnosis varied by hospital, particularly malaria – some hospitals had very few malaria cases while at others, 60-70% of admitted children had malaria. Pneumonia rates also varied across hospitals, while diarrhoea rates did not. When examining the diagnoses as a proportion of admissions by hospital it initially appears as though the pneumonia rates are lowest in the hospitals where the malaria rates are highest; however, this association is dampened when one examines the absolute number of admissions with each diagnosis (see Table 5.1), indicating that when there are many malaria admissions, these 'crowd out' other admissions which then represent a smaller proportion of total admissions. We have no population-based measures so we are not able to determine whether the incidence of pneumonia is lower, higher or the same in areas with high vs. low incidence of malaria. The hospital with the lowest pneumonia rate (Hospital 3: 25%) was that at which the percent of children with a pulse oximeter value below 90% was lowest (5%), while the converse was also the case (Hospital 6: 56% pneumonia and 20% children had an oxygen saturation value <90%).

In some hospitals, pneumonia rates varied across months, potentially indicating seasonality of the disease, although the months in which pneumonia rates were highest vs. lowest were different for different hospitals, probably because climate, environmental, social, and economic factors vary across the country.[Ayieko et.al.2012] (See Figure 5.9) As these analyses involved data over two years, annual seasonal variations would have been captured and so should not unduly influence the results.

Figure 5.6: Percent of admitted children with each diagnosis

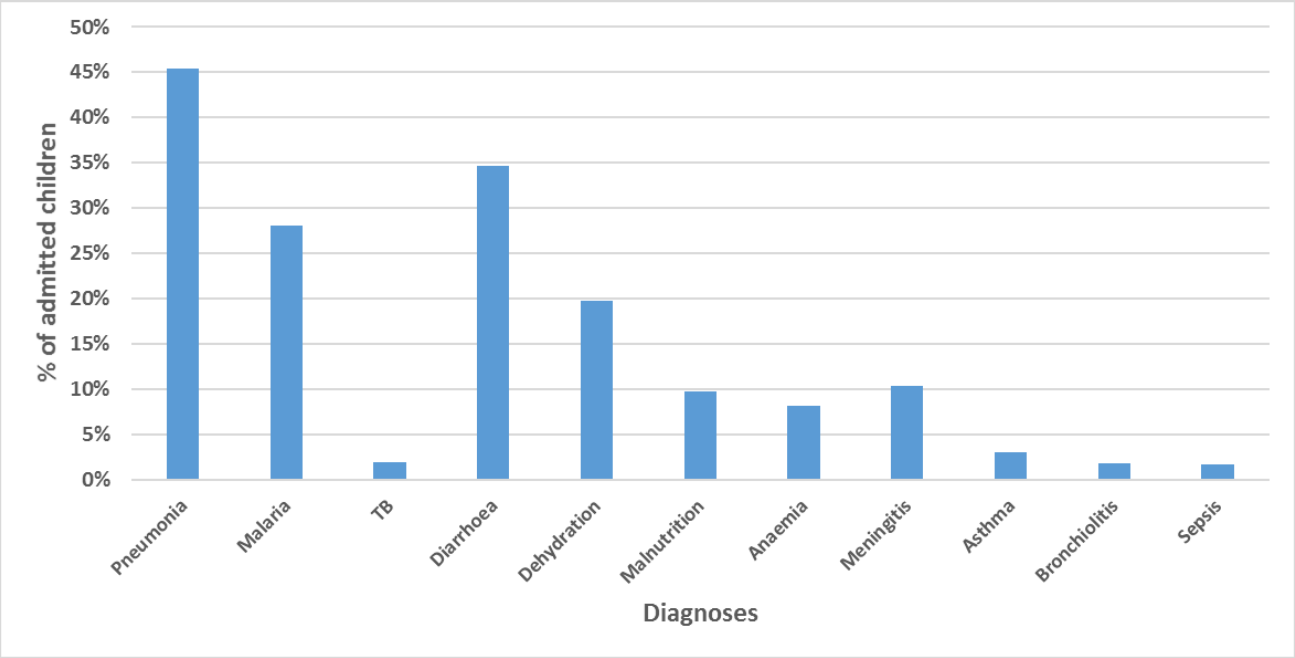
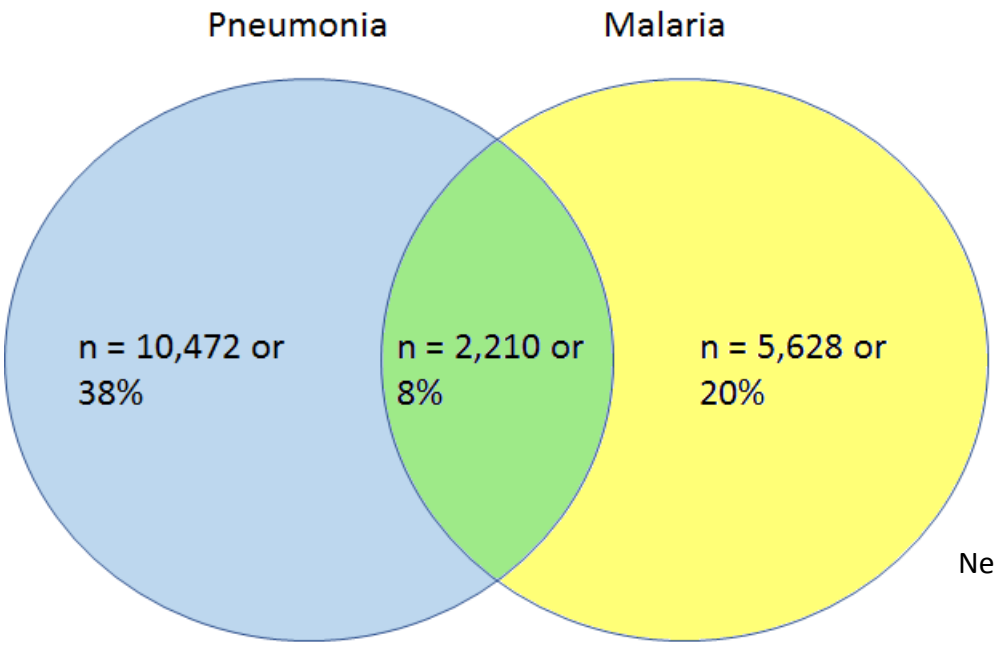


Figure 5.7: Venn diagram showing the number and percent of children with pneumonia and malaria



Neither: 9,604 or 34%

Figure 5.8: Percent of children with pneumonia, malaria and diarrhoea by hospital

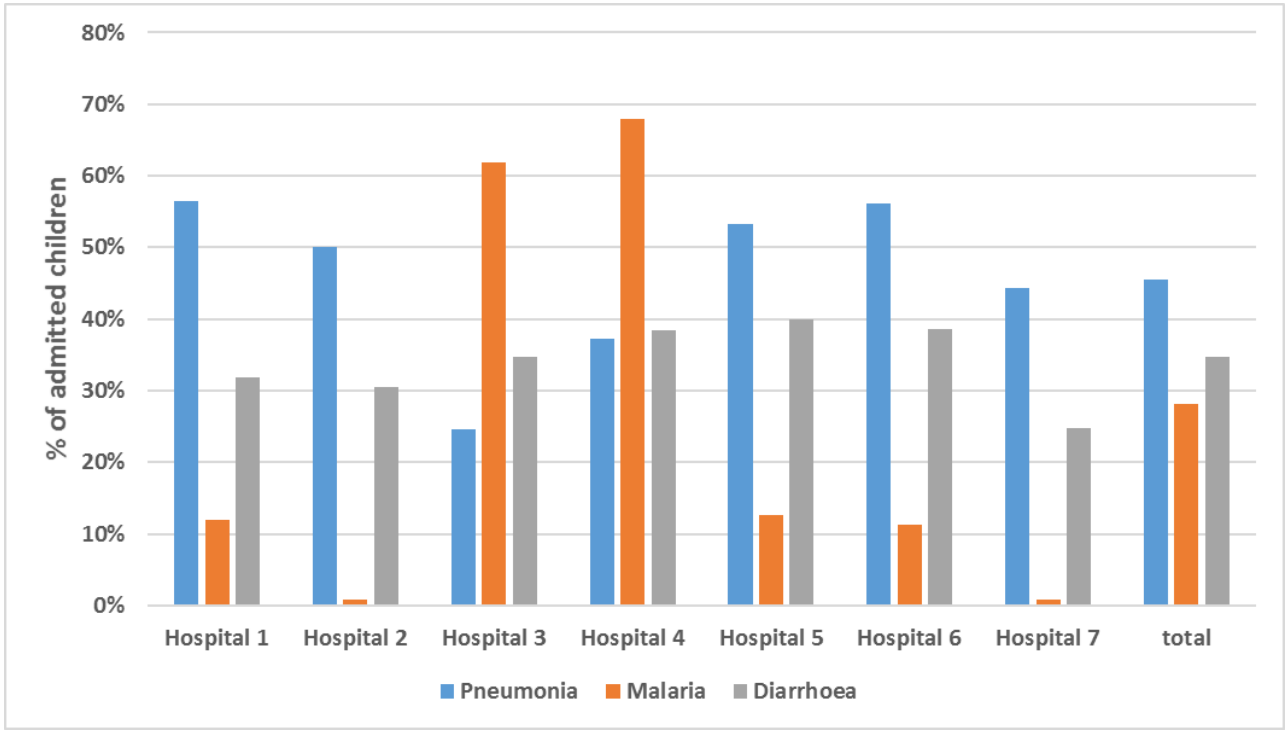
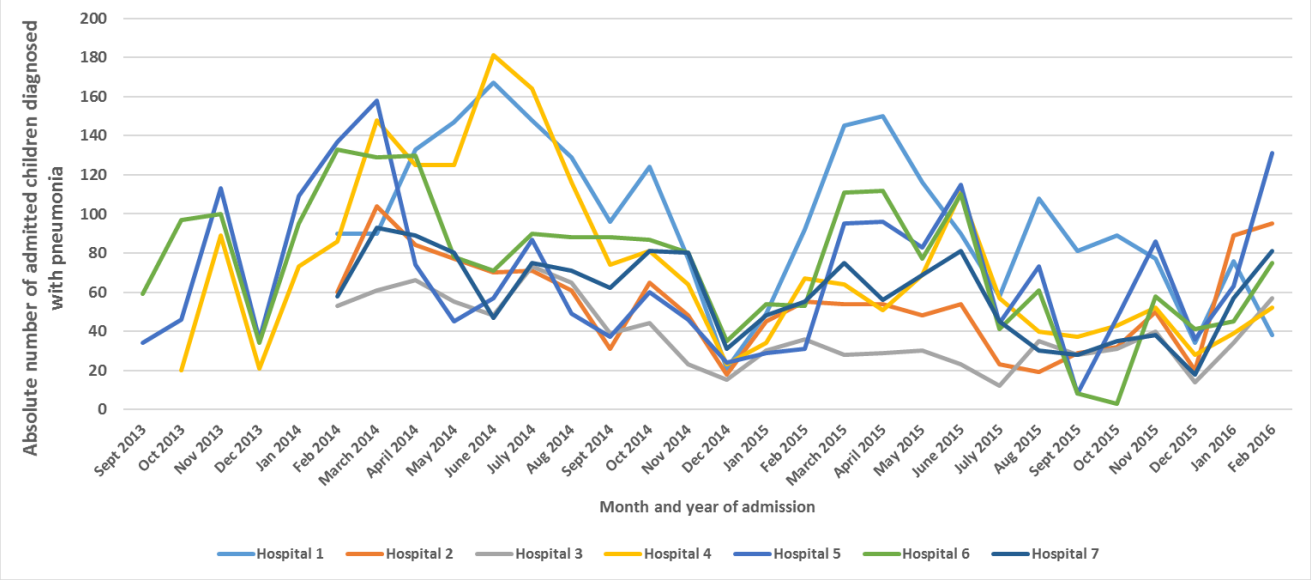


Figure 5.9: Number of admitted children diagnosed with pneumonia over time by hospital



Note: hospitals entered in to the CIN at different months (all had entered by February 2014), so lines in Figure 5.9 begin at different dates; the drop in December is due to a drop in total admissions recorded because the data clerks go on vacation in December

vi) Oxygen

Approximately 8% of children were recorded as being prescribed oxygen; 15% of children with pneumonia, and 2% of children without pneumonia, were recorded as being given oxygen.

Of the 6,464 children with pneumonia who had a pulse oximeter reading, 12% (609/5,264) of those with a reading ≥90% were given oxygen, compared with 34% (413/1,200) of those with a reading <90%. Of the 6,892 children without pneumonia who were given a pulse oximeter reading, 2% (112/6,584) of those with a reading ≥90% were given oxygen, compared with 22% (69/308) of those with a reading <90%. (See Figure 5.10) It is unsurprising that, regardless of the value of their pulse oximeter reading, children with pneumonia were given oxygen more often than children without pneumonia, because the clinical signs indicating that a child has pneumonia are often the same clinical signs that indicate a need for oxygen. In making comparisons, it is however important to consider the relative levels of oxygen use, rather than the absolute values, given the limitations of the oxygen documentation (see Section 7.3.3).

Just as pulse oximetry patterns were similar in children with vs. without pneumonia (see Figure 5.5), children with pneumonia also had similar patterns of oxygen provision over time as those without pneumonia (see Figure 5.11). As with the pulse oximetry patterns, this could suggest that oxygen provision over time may be impacted by factors external to the patients, e.g. hospital characteristics (procurement and repair processes, staffing levels, infrastructure issues, etc.). However, the overall trend in oxygen provision over time was not similar to that of pulse oximeter use which had a clear temporal trend; this suggests that increased pulse oximeter use is not necessarily increasing oxygen prescription, although it might be improving targeting of oxygen use.

Figure 5.10: Percent of children with and without pneumonia and with pulse oximeter values <90% vs. ≥90% prescribed oxygen

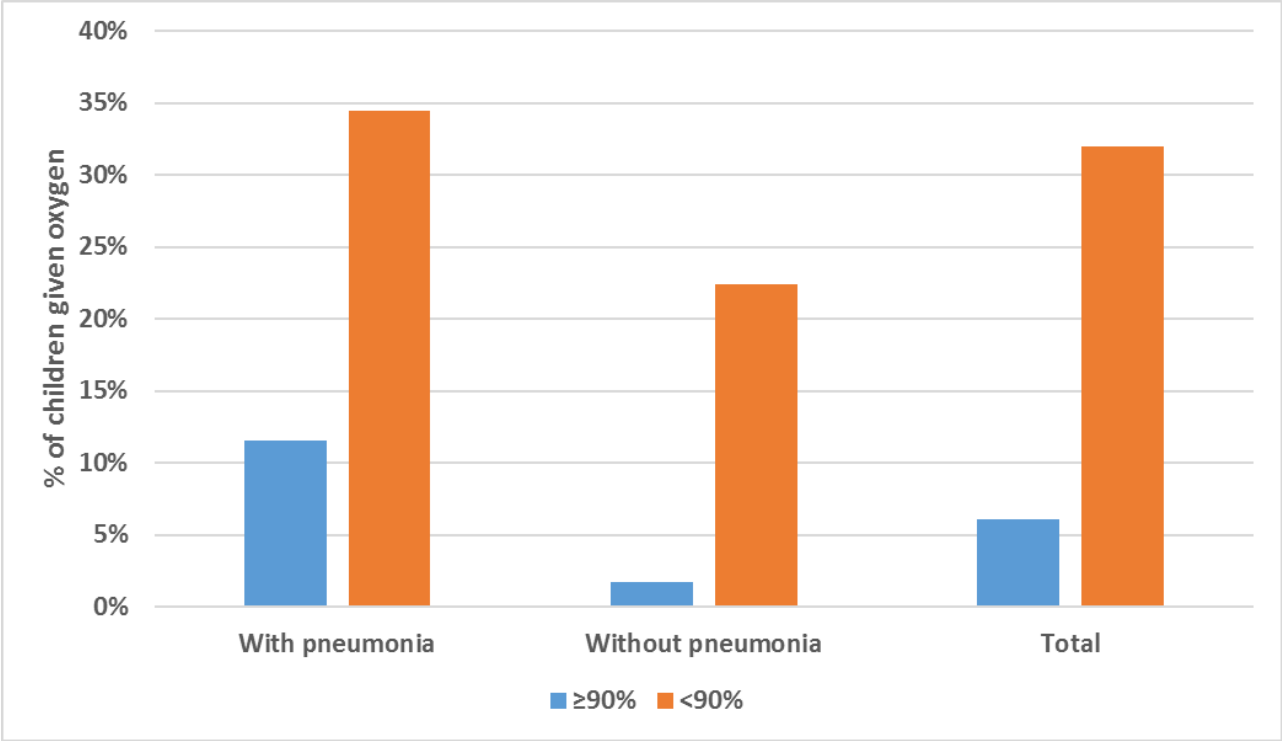
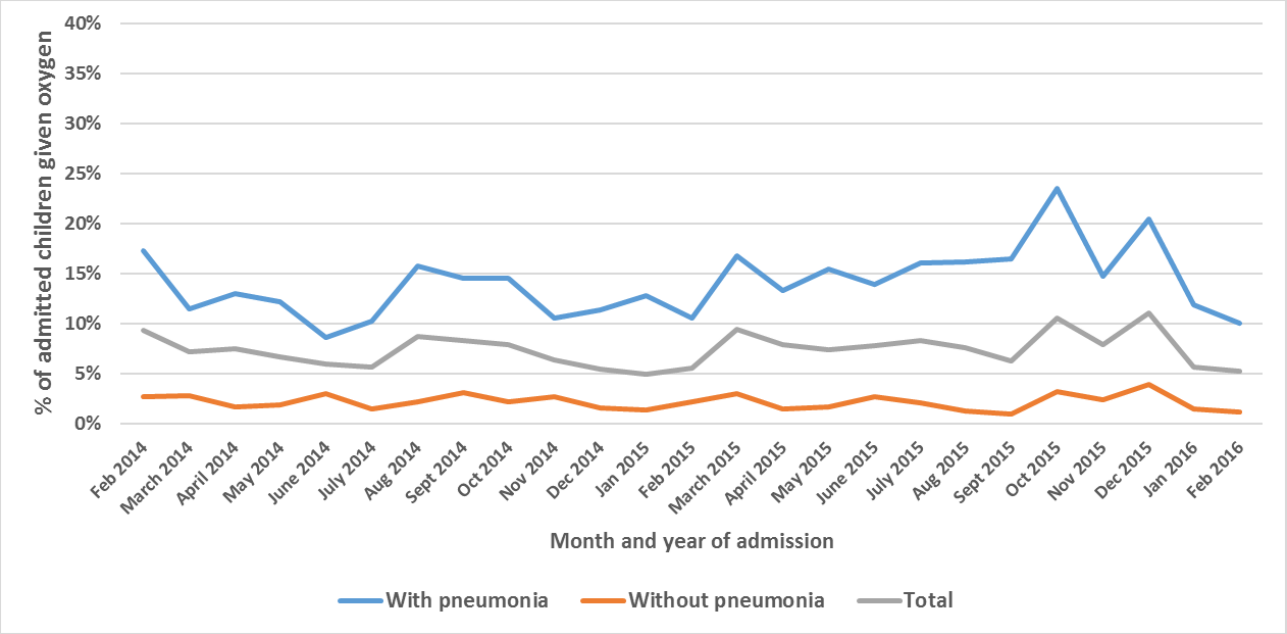


Figure 5.11: Over time, the percent of all children and of those with and without pneumonia who were given oxygen



Note: The figure begins in February 2014 because hospitals joined the CIN in different months, and all had joined by February 2014.

vii) Outcome

Approximately 6% of admitted children died; 8% and 5% of children with and without pneumonia, respectively, died.[4] Table 5.1 also shows that the mortality rates vary substantially by hospital (range 2-10%); this range may be caused by differences in care quality, the conditions with which children present to the hospitals, and the children's socioeconomic characteristics.

5.3 Missing data patterns

[4] There is extensive evidence that hypoxemia increases risk of death (see Section 1.1.3); the link of hypoxemia with mortality was not however the subject of analysis of this research.

5.3.1 Amount of missing data for each variable

Both outcomes of interest (*Pulse oximeter use* and *Oxygen use*) had less than 5% missing data. Most variables, including *Pulse oximeter value*, had less than 10% missing data. Symptoms tended to have higher missing data levels (most had 10-15% missing data) than demographic variables (most had <5% missing data). Only four variables had 15% or more missing data (*Difficulty drinking, PAR use*[5]*, Very high respiratory rate,* and C*apillary refill*) and none had more than 25% missing data. As the threshold for excluding variables from the analyses was 40% missing data (see Section 3.9.2), no variables were excluded. (Appendix 5.3 contains the levels of missing data for each variable.)

5.3.2 Number of missing values per person

Children in the dataset had a median of 1 missing value out of the 45 variables examined, with an IQR of 0-2, range: 0-28, mean: 3.2. The majority of children had 0 or 1 missing values (see Figure 5.12).

The average number of missing values per person varied by hospital and time, as shown in Figure 5.13. Overall, missingness decreased over time.

There were minor differences between children with vs. without missing data, and these differences were explainable. For instance, a PAR was more likely to be used with a child with complete data than with a child with missing data, which is not surprising as the PAR promotes more thorough data recording.[Gachau et.al.2017] Appendix 5.4 contains more details.

[5] The Paediatric Admission Record (PAR) is an admissions form used to record medical information; it was implemented to improve recording of this information and to prompt recommended behaviour

We can see from these descriptions of the missing data patterns that missingness levels were not so extreme as to question the data's quality, but missingness was frequent enough that multiple imputation could result in a valuable increase in use of available data.

Figure 5.12:

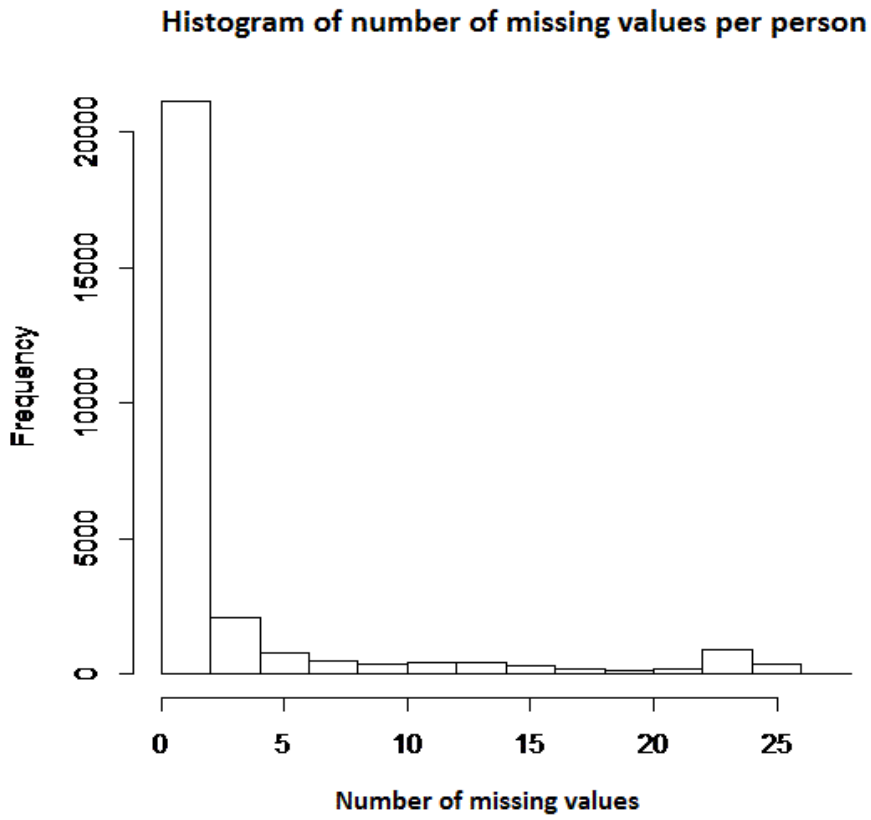
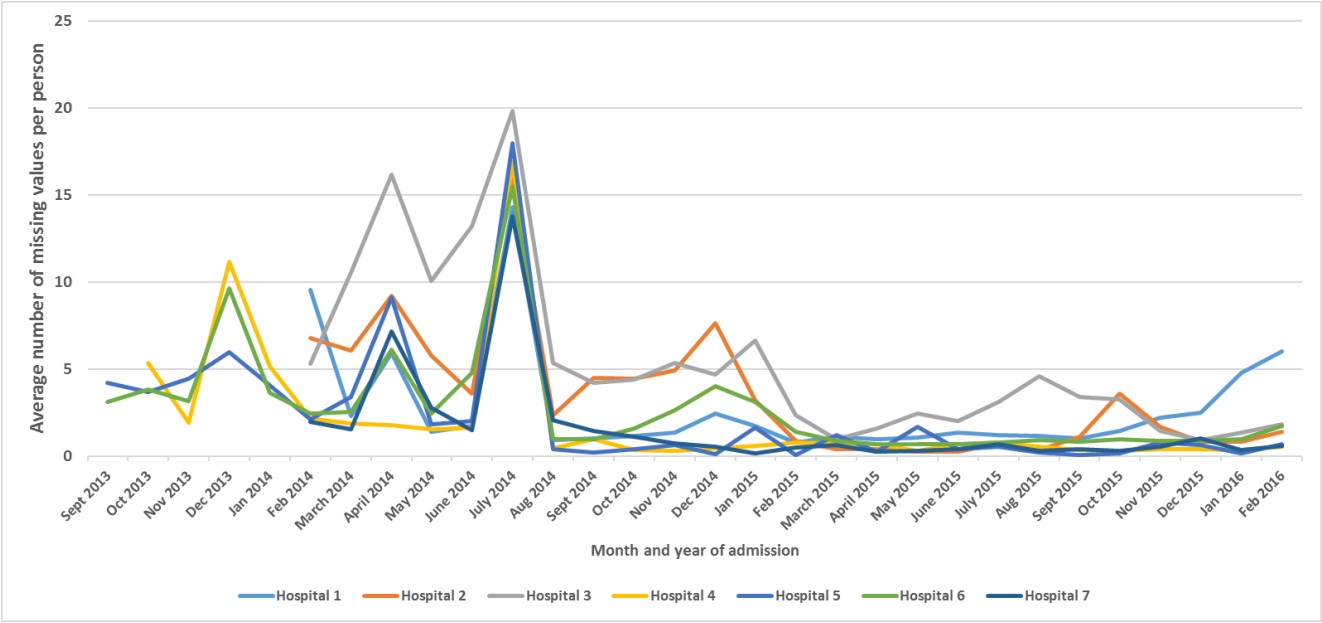


Figure 5.13: Average number of missing values per person over time by hospital



Note: hospitals entered in to the CIN at different months (all had entered by February 2014), so lines in Figure 5.13 begin at different dates; the peak in July 2014 might be related to the rotation of medical staff on the wards – a similar pattern did not occur in subsequent years as better use of PAR had become more embedded.

5.4 Multiple imputation

5.4.1 MAR vs. MNAR

According to Chi-squared analyses (for the categorical variables) and regression (for the continuous variables), there was a significant association ($p<0.05$) between missingness levels and values of *Admission month*, *Age*, and *PAR use*, but no association for values of W*eekend admission*, *Admission time period* (admission coded according to the 6-month interval in which the admission date occurred), *Hospital*, *Sex*, *Outcome, Pulse oximeter use* or *Oxygen use*. Appendix 5.5 contains figures and values for these analyses.

Therefore, as I had identified factors that could help explain the missing data levels and patterns, it is likely that the data were Missing At Random. I therefore included the *Admission month*, *Age*,

and *PAR use* variables in the multiple imputation process, to ensure that their effect on missingness levels was taken into account in creating estimates for the missing values.[Sterne,2009] (See Section 3.10.2)

5.4.2 Convergence

For each of the three datasets (one for each Research Question), the coefficients and confidence intervals calculated by running the full regression models with 10 imputed datasets vs. 30 imputed datasets were very similar (e.g. all pairs of confidence intervals overlapped extensively, and on average, coefficients differed by 0.01). Appendix 5.6 contains a comparison of these values. This suggested that running more imputations would be unlikely to change the results, i.e. that convergence had occurred.

In addition, figures of the mean and standard deviation for all variables across the iterations of the 30 imputations displayed intermingling streams without definite trends, indicating convergence had been achieved.[van Buuren&Groothuis-Oudshoorn,2011] (Appendix 5.7 contains figures displaying this, and Section 3.10.5 explains how I chose which methods to use to determine if convergence was achieved)

Although 10 imputations would therefore likely have been sufficient, I decided to be conservative in my choice and carried out 30 imputations for each of the three Research Question datasets, to maximize the likelihood of convergence.

Various sensitivity analyses were conducted to check for bias in the imputed data due to violation of the MAR assumption. (See Appendix 5.8) Based on these, we can conclude that the multiple imputation process accurately retained the existing data's characteristics in estimating the missing values.

Once multiple imputation and its associated sensitivity analyses were complete, I could carry out logistic regressions for each Research Question.

5.5 Research Question 1: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

5.5.1 Selecting the variables for the reduced model

I developed two reduced models, one through manual backwards stepwise regression, the other through using bootstrap AIC; Section 3.11.5 discusses these methods in detail; Appendix 5.9 contains multicollinearity analyses.

Using manual backwards stepwise regression, I developed the following logistic regression model:

Pr(Pulse oximeter use) = Hospital + Sex + Age + Weight-for-age + Admission time period + Hospital use of pulse oximeters by admission month + PAR use + Weekend admission + Fever + Cough + Difficulty breathing + Vomit everything + Very high respiratory rate + Indrawing + Difficulty drinking + Lack of alertness + Indrawing x Lack of alertness

I developed the following model by including variables that appeared in, on average, 50% or more of the models produced by running stepwise selection using AIC on all 30 imputed datasets, and on 30 bootstrapped-derived datasets from each of 3 imputed datasets:

Pr(Pulse oximeter use) = Hospital + Sex + Age + Weight-for-age + Admission time period + Hospital use of pulse oximeters by admission month + PAR use + Weekend admission + Fever + Cough + Difficulty breathing + Vomit everything + Difficulty feeding + Convulsions + Very high

respiratory rate + Cyanosis + Indrawing + Grunting + Crackles + Difficulty drinking + Lack of alertness + Length of illness before admission + Cyanosis x Difficulty feeding + Indrawing x Lack of alertness + Very high respiratory rate x Difficulty feeding

Thus, we can see that all the variables included in the manual model were also included in the AIC model but the AIC model includes additional variables (*Difficulty feeding*, *Convulsions*, *Cyanosis*, *Grunting*, *Crackles*, *Length of illness before admission*, *Difficulty feeding x Cyanosis* and *Very high respiratory rate x Difficulty feeding*).

However, when these models were separately run with each of the 30 imputed datasets and the results were pooled using Rubin's rules, the odds ratios and confidence intervals of the variables included in both models were almost exactly the same, and none of the variables that were only included in the AIC model were statistically significant (based on confidence interval spread). The results I present are therefore from the manual model.

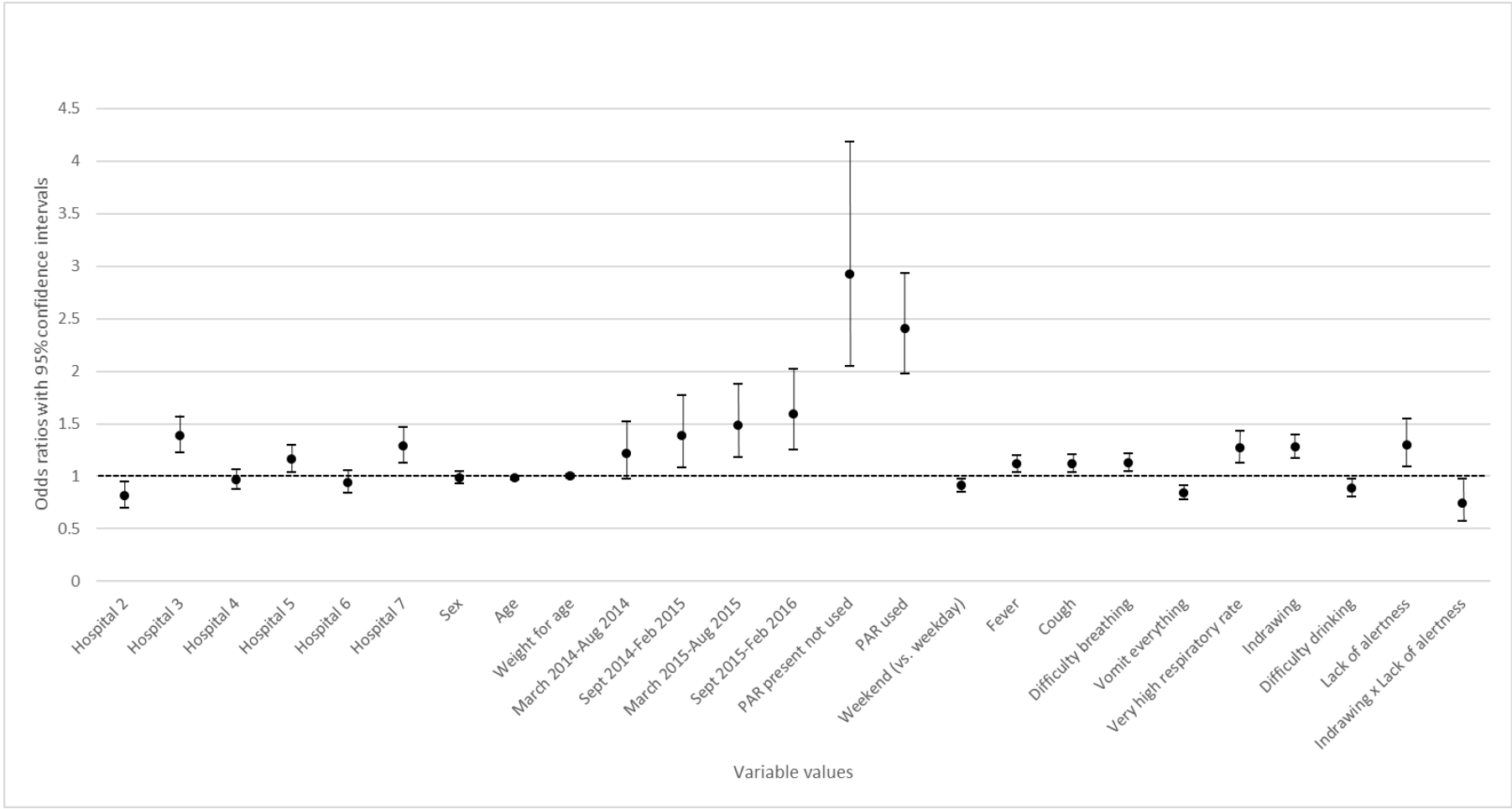
5.5.2 Results: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

According to these multivariable analyses, when all other variables were held constant, a pulse oximeter was significantly more likely to be used when the child was younger; admitted on a weekday; had a fever, cough, difficulty breathing, and/or a very high respiratory rate; was not vomiting everything, did not have difficulty drinking; and/or had indrawing or was not alert, but did not have both of these symptoms; pulse oximetry was also significantly more likely in certain hospitals and when a PAR was present, whether or not it was used; and the likelihood of obtaining a pulse oximeter reading increased over the study time period. Figure 5.14 displays each variable's odds ratio and confidence interval while Appendix 5.10 contains a table of these; Table 5.4 shows each Research Question's main findings.

Of these, the factors that were most influential on whether a pulse oximeter was used were *Hospital*, *Admission time period*, *PAR use*, *Very high respiratory rate* (OR: 1.27, 95% CI: 1.13, 1.43), *Indrawing* (OR: 1.28, 95% CI: 1.17, 1.40), *Lack of alertness* (OR: 1.30, 95% CI: 1.09, 1.55), and the interaction between *Indrawing* and *Lack of alertness* (OR: 0.75, 95% CI: 0.57, 0.98).

When the model was run separately for each hospital, there were differences across the hospitals in terms of the odds ratios' magnitude, direction of effect, and significance (based on confidence interval spread), even for variables found to be very influential when admissions from all hospitals were analysed together (Appendix 5.11 contains the results). This is an example of the Simpson Yule Paradox, which describes how sometimes when data are aggregated, a trend emerges which does not follow, and may even contradict, the trends produced when subsets of the data (e.g. different groups, settings, time periods) are analysed separately.[Goltz&Smith,2010; Hernan et.al.2011] The Simpson Yule Paradox is not a concern in this situation because any confounding that it could have suggested by the hospital variable in the aggregated data was prevented by controlling for the hospital variable in the regressions. This sensitivity analysis shows that there are differences between the hospitals, but we cannot conclude anything more definitive based on it.

Figure 5.14: Odds ratios of each variable when 'best model' run for Research Question 1: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?



Note: *Hospital use of pulse oximeters by admission month* is not included in the figure because this variable was only included to control for it, and its odds ratios are very large because the variable is directly related to pulse oximeter use, and so including the variable would skew the figure. Appendix 5.10 shows values and baseline designations.

5.5.3 Pneumonia analyses: Are the results different for children who have vs. do not have pneumonia?

Hospital, *PAR use*, and *Lack of alertness* were important factors in predicting pulse oximeter use in children who did have pneumonia as well as in children who did not have pneumonia, but there were also many differences between the models produced for the two groups of children. Table 5.2 explores these similarities and differences. Appendix 5.12 contains the odds ratios and confidence intervals.

Table 5.2: Which variables significantly impacted pulse oximeter use for children with vs. without pneumonia

Variable	Significant for children with pneumonia	Significant for children without pneumonia
Hospital	√	√
Sex		
Age		√ (-)
Weight-for-age		
Admission time period	√	√
PAR use	√	√
Weekend admission	√ (-)	
Fever		√ (+)
Cough		√ (+)
Vomit everything		√ (-)
Very high respiratory rate	√ (+)	√ (+)
Cyanosis	√ (+)	
Indrawing	√ (+)	
Wheeze		√ (+)
Difficulty drinking	√ (-)	
Lack of alertness	√ (+)	√ (+)
Cyanosis x Indrawing	√ (-)	
Indrawing x Lack of alertness	√ (-)	

'+' and '-' symbols indicate direction of effect of significant odds ratios (significance is based on confidence intervals not crossing 1) of dichotomous and continuous variables; shaded variables are those for which there is a difference between children with vs. without pneumonia; these models are those produced through manual backwards stepwise regression (the manual model and bootstrap AIC models were very similar, and so the manual model was chosen, to be consistent with the main analyses done for Research Question 1 on all children).

5.6 Research Question 2: Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?

5.6.1 Selecting the variables for the reduced model

Appendix 5.9 contains multicollinearity analyses.

Using manual backwards stepwise regression, I developed the following logistic regression model:

Pr(Oxygen use) = Pulse oximeter use + Hospital + Sex + Age + Weight-for-age + Admission time period + Hospital use of pulse oximeters by admission month + PAR use + Weekend admission + Fever + Cough + Difficulty breathing + Vomit everything + Difficulty feeding + Convulsions + Very high respiratory rate + Cyanosis + Indrawing + Grunting + Crackles + Difficulty drinking + Pallor + Lack of alertness + Length of illness before admission + Pneumonia diagnosis + Malaria diagnosis + TB diagnosis + Diarrhoea diagnosis + Dehydration diagnosis + Malnutrition diagnosis + Anaemia diagnosis + Meningitis diagnosis + Asthma diagnosis + Bronchiolitis diagnosis + Sepsis diagnosis + Antimalarials

The only difference of the model obtained through the bootstrap AIC method, was that the bootstrap AIC model also contained *Stridor*; however, the *Stridor* variable was not significant (p=0.058, OR 95% CI: 0.99,1.57), and the rest of the variables had very similar coefficients and confidence intervals in both models. The results I present are therefore from the manual model.

5.6.2 Results: Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?

Pulse oximeter use was a significant predictor of oxygen provision ($p=1*e^{-7}$). Children were 42% more likely to be prescribed oxygen if they were given a pulse oximeter reading[6] than if they were not given a pulse oximeter reading (OR: 1.42, 95% CI: 1.25, 1.62).

In addition, oxygen was significantly more likely to be prescribed when the child was younger; had not been ill for four or more days before admission; had difficulty breathing, a very high respiratory rate, cyanosis, indrawing, grunting, crackles, difficulty drinking, and/or pallor; did not have a fever, was not alert; had pneumonia, anaemia, asthma, bronchiolitis and/or sepsis, but not diarrhoea or malnutrition; the hospital and admission time period also significantly impacted the likelihood that oxygen was given.

Of these, the demographic factors that were most influential on whether oxygen was given were *Hospital* and *Admission time period*; of the symptoms, the most influential were D*ifficulty breathing* (OR: 2.00, 95% CI: 1.76, 2.28), *Indrawing* (OR: 2.68[7], 95% CI: 2.33, 3.09), and *Cyanosis* (OR: 1.92, 95% CI: 1.34, 2.76); and the most influential diagnoses were *Asthma diagnosis* (OR: 1.94, 95% CI: 1.59, 2.35) *Bronchiolitis diagnosis* (OR: 1.88, 95% CI: 1.47, 2.41) and *Pneumonia diagnosis* (OR: 1.76, CI: 1.49, 2.07). Figure 5.15 displays each variable's odds ratio and confidence interval while a table of these is found in Appendix 5.13.

These findings are largely consistent with the guidelines of the WHO's 2016 Oxygen Therapy for Children manual, which says that the signs of hypoxemia (and thus a need for oxygen), in addition to a pulse oximeter reading below 90%, are cyanosis, nasal flaring (not measured in this dataset), difficulty drinking or feeding (if because of respiratory distress), grunting and depressed mental state (equivalent to the *Lack of alertness* variable in this dataset); of these,

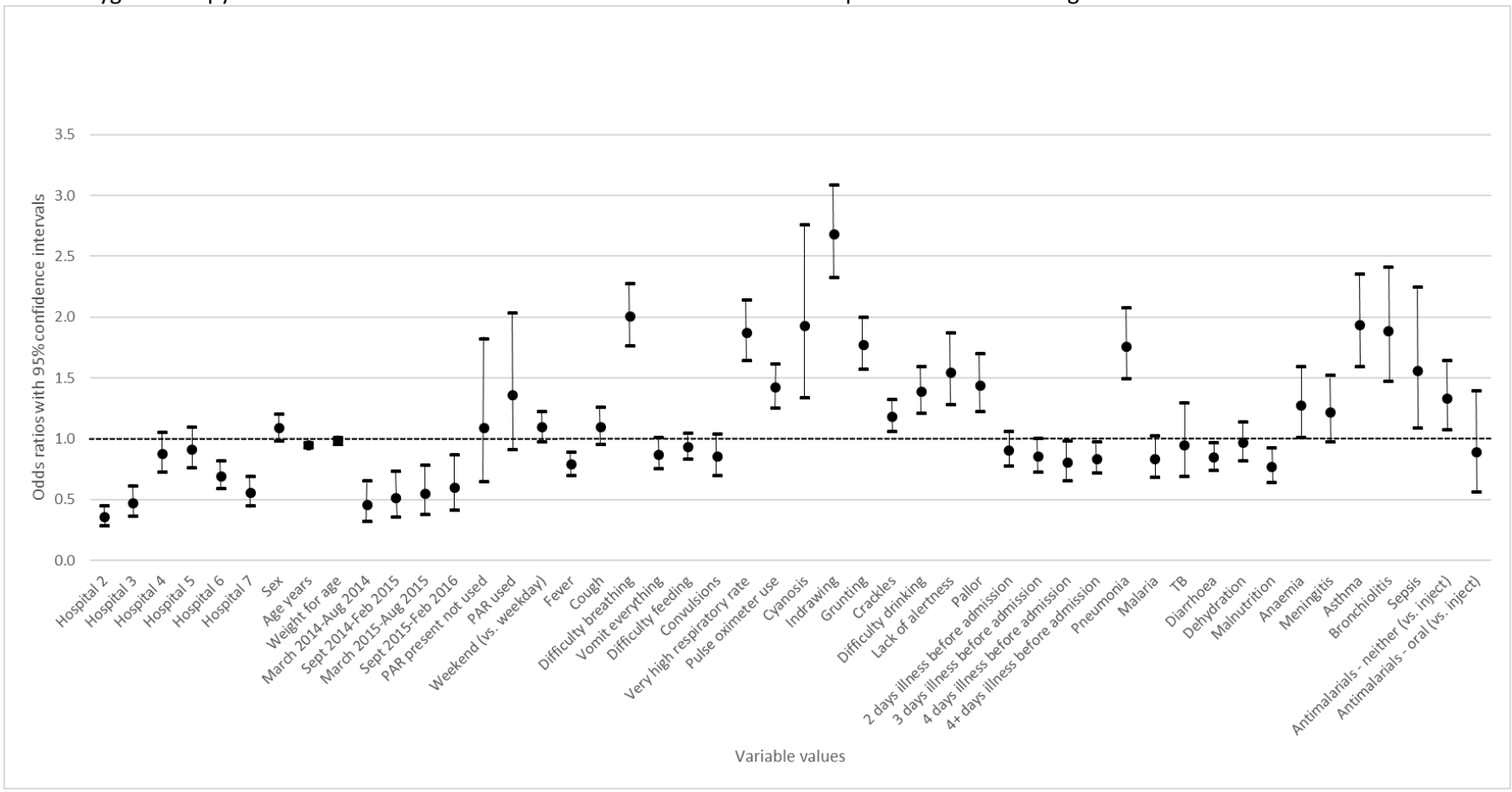
[6] To clarify, this is if a child obtained any pulse oximeter reading, not just if they obtained a low pulse oximeter reading.

[7] This is a large odds ratio, and there is discussion in the literature over whether and how large odds ratios over-estimate the relative risk. However, in this case, as the risk of the event occurring (e.g. of a child with indrawing being given oxygen) is low (20%), the over-estimation is unlikely to be substantial and so is not a concern. [Davies et.al.1998] (See Section 7.3.3)

only difficulty feeding was not influential according to these findings. The manual also states that in some situations and depending on the child's condition, indrawing and a high respiratory rate are also good indicators of hypoxemia, which is consistent with the actions of HCWs in this dataset. Cough and convulsions were not found to significantly impact oxygen provision, which is understandable as, although these symptoms can be associated with conditions necessitating oxygen, they can also be due to various other causes.

The WHO recommends giving oxygen to children with severe forms of pneumonia, bronchiolitis and asthma [WHO,2013] (and children admitted to hospital with these conditions are likely to have severe forms), so the HCWs in this dataset are acting in accordance with these recommendations too. However, recommendations do not say that oxygen is needed for children with anaemia or sepsis, but the findings suggest that HCWs in these hospitals were more likely to give oxygen to children with these diagnoses than to children without. (Other diagnoses and symptoms were controlled for in the regression so this finding is not due to comorbidities.)

Figure 5.15: Odds ratios of each variable when 'best model' run for Research Question 2: Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?



Note: *Hospital use of pulse oximeters by admission month* is not included in the figure because this variable was only included to control for it, and its odds ratios are very large because the variable is directly related to pulse oximeter use, and so including the variable would skew the figure. Appendix 5.13 shows values and baseline designations.

5.6.3 Pneumonia analyses: Are the results different for children who have vs. do not have pneumonia?

Pulse oximeter use was a significant predictor of oxygen provision in children with and without pneumonia ($p=5*10^{-6}$, p=0.03, respectively). Children with and without pneumonia were 39% and 41% more likely, respectively, to be prescribed oxygen if they obtained a pulse oximeter reading than if they did not obtain one (OR: 1.39, 95% CI: 1.21, 1.61, and OR: 1.41, 95% CI: 1.04, 1.90, respectively).

Many variables significantly impacted the likelihood of oxygen use in all children, regardless of whether they had pneumonia or not: *Hospital*, *Age*, *Admission time period*, *Fever*, *Difficulty breathing*, *Very high respiratory rate*, *Cyanosis*, *Indrawing*, *Crackles*, *Difficulty drinking*, *Asthma diagnosis,* and *Bronchiolitis diagnosis*. However, there were also several differences between the models of the two groups of children. Table 5.3 explores these similarities and differences. Odds ratios and confidence intervals are in Appendix 5.14.

Table 5.3: Which variables significantly impacted oxygen use for children with vs. without pneumonia

Variable	Significant for children with pneumonia	Significant for children without pneumonia
Hospital	√	√
Sex		
Age	√ (-)	√ (-)
Weight-for-age		
Admission time period	√	√
PAR use		
Fever	√ (-)	√ (-)
Difficulty breathing	√ (+)	√ (+)
Very high respiratory rate	√ (+)	√ (+)
Pulse oximeter use	√ (+)	√ (+)
Cyanosis	√ (+)	√ (+)
Indrawing	√ (+)	√ (+)
Grunting	√ (+)	
Crackles	√ (+)	√ (+)
Difficulty drinking	√ (+)	√ (+)

Pallor	√ (+)	
Lack of alertness		√ (+)
Length of illness before admission		√
Malaria diagnosis		√ (-)
TB		
Diarrhoea diagnosis		√ (-)
Dehydration		
Malnutrition diagnosis	√ (-)	
Anaemia diagnosis		√ (+)
Meningitis		
Asthma diagnosis	√ (+)	√ (+)
Bronchiolitis diagnosis	√ (+)	√ (+)
Sepsis diagnosis		√ (+)
Antimalarials	√	

'+' and '-' symbols indicate direction of effect of significant odds ratios (significance is based on confidence intervals not crossing 1) of dichotomous and continuous variables; shaded variables are those for which there is a difference between children with vs. without pneumonia; these models are those produced through manual backwards stepwise regression (the manual model and bootstrap AIC models were very similar, and so the manual model was chosen, to be consistent with the main analyses done for Research Question 2 on all children).

5.7 Research Question 3: Are pulse oximeter readings below 90% associated with the prescription of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?

5.7.1 The model used

For Research Question 3, I used the model developed for Research Question 2, with the exception that *Pulse oximeter value* was included instead of *Pulse oximeter use*, to control for all variables, other than pulse oximeter use, that influence oxygen provision, so as to determine how HCWs' decision to use oxygen is determined by a high vs. low pulse oximeter value. (Appendix 5.9 contains multicollinearity analyses.)

5.7.2 Results: Are pulse oximeter readings below 90% associated with the prescription of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?

After controlling for all other factors, the value of the pulse oximeter reading was a significant predictor of oxygen provision ($p<1*e^{-10}$). Children were more than twice as likely to obtain oxygen if they had a pulse oximeter reading below 90% than if they had a pulse oximeter reading of 90% or more (OR: 3.29, 95% CI: 2.82, 3.84). This suggests that HCWs may be using the recommended 90% threshold to help decide whether to prescribe oxygen.

5.7.3 Pneumonia analyses: Are the results different for children who have vs. do not have pneumonia?

Children with a pulse oximeter reading below 90% were significantly more likely to obtain oxygen than children with higher pulse oximeter readings, regardless of whether they had pneumonia or not ($p<1*e^{-10}$ in both cases). Children with pneumonia were almost twice as likely to be prescribed oxygen if their pulse oximeter reading was below 90% than if it was 90% or above, while children without pneumonia whose pulse oximeter reading was less than 90% were more than six times as likely to obtain oxygen than those with readings of 90% or higher (OR: 2.89, 95% CI: 2.45, 3.40, and OR: 7.28, 95% CI: 4.74, 11.19, respectively). The higher odds ratio in children without pneumonia may be because, in children without pneumonia, a reading of <90% is more likely to be the only sign indicating a need for oxygen than in children with pneumonia, who are likely to have other respiratory symptoms suggesting a need for oxygen.

5.8 Key Research Question findings

Table 5.4: Key findings for each Research Question

Research Questions	Key findings
Research Question 1: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?	Variables found to be most influential in impacting pulse oximeter use: • *Hospital* • *Admission time period* • *PAR use* • *Very high respiratory rate* (OR: 1.27, 95% CI: 1.13, 1.43) • *Indrawing* (OR: 1.28, 95% CI: 1.17, 1.40) • *Lack of alertness* (OR: 1.30, 95% CI: 1.09, 1.55) • *Indrawing x Lack of alertness* (OR: 0.75, 95% CI: 0.57, 0.98)

Research Question 2: Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?	Children who obtained a pulse oximeter reading were significantly more likely to be prescribed oxygen than children who did not obtain a pulse oximeter reading (OR: 1.42, 95% CI: 1.25, 1.62)
	
	Other variables found to be most influential in impacting oxygen provision:
	• Demographic factors:
	  ○ *Hospital*
	  ○ *Admission time period*
	• Symptoms:
	  ○ *Difficulty breathing* (OR: 2.00, 95% CI: 1.76, 2.28)
	  ○ *Indrawing* (OR: 2.68[i], 95% CI: 2.33, 3.09)
	  ○ *Cyanosis* (OR: 1.92, 95% CI: 1.34, 2.76)
	• Diagnoses:
	  ○ Asthma (OR: 1.94, 95% CI: 1.59, 2.35)
	  ○ Bronchiolitis (OR: 1.88, 95% CI: 1.47, 2.41)
	  ○ Pneumonia (OR: 1.76, CI: 1.49, 2.07)

Research Question 3: Are pulse oximeter readings below 90% associated with the prescription of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?	Children were significantly more likely to obtain oxygen if they had an oxygen saturation below 90% than if they had an oxygen saturation of 90% or more (OR: 3.29[i], 95% CI: 2.82, 3.84)
Secondary Research Question: Are the results for Research Questions 1-3 different for children who have vs. do not have pneumonia?	• Children with pneumonia who obtained a pulse oximeter reading often had different characteristics than the children without pneumonia who obtained a pulse oximeter reading. • Children were more likely to be prescribed oxygen if they had obtained a pulse oximeter reading than if they had not, regardless of whether they had pneumonia or not (OR: 1.39, 95% CI: 1.21, 1.61 and OR: 1.41, 95% CI: 1.04, 1.90,

	respectively). There were several differences between children with vs. without pneumonia, in terms of the other variables that significantly impacted the likelihood of oxygen provision. • Children with oxygen saturation <90% were significantly more likely to be prescribed oxygen than children with a pulse oximeter reading ≥90%, regardless of whether they had pneumonia or not (OR: 2.89[i], 95% CI: 2.45, 3.40, and OR: 7.28[i], 95% CI: 4.74, 11.19, respectively)

[i] These are large effects and so there is a possibility that they have been over-estimated, see 7.3.3

Appendix 5.10 and 5.13 contain odds ratios and confidence intervals for all variables for Research Question 1 and 2.

Although pulse oximetry is not uniform as guidelines recommend, pulse oximeter use is increasing, and the associations of particular clinical signs/symptoms with pulse oximetry and oxygen prescription suggest guideline influence. Non-adherence to universal pulse oximetry appears to be driven at least partly by clinical signs/illness type. Increased pulse oximetry is associated with increased oxygen provision, suggesting that pulse oximetry helps guide oxygen prescription. Furthermore, the pulse oximeter value analyses suggest the recommended threshold (<90%) is influential. Nonetheless, many of those with readings <90% are still not obtaining oxygen. Decision-making across the clinical process differs by hospital and admission time period, while the PAR reminds HCWs to use pulse oximeters. Alternatively, PAR use may be a marker of HCWs who are more adherent to recommendations. The findings support Figure 3.3's conceptual models, as they suggest clinical signs/symptoms guide diagnostic test choice (some of the signs/symptoms in Figure 3.3b were particularly influential), and the test results guide treatment. The qualitative research described in Chapter 6 explored and expanded upon these findings.

Chapter 6: Results for qualitative analyses

6.1 Overview

6.1.1 The quantitative research results

My findings from analysing the Clinical Information Network (CIN) dataset of 27,914 children admitted to seven CIN hospitals[8] with any diagnosis from September 2013-February 2016 (see Chapters 3 and 5), are shown in Box 6.1.

Box 6.1: summary of findings from the quantitative analyses of the CIN data

- There was substantial variability in pulse oximeter use within and across the 14 CIN hospitals. Across the seven hospitals included in the analyses, the percent of children on average with whom pulse oximeters were used over the study period ranged from 21%-75%, while within hospitals, pulse oximeter use could drop from 93% in one month to 7% two months later. (See Appendix 3.1 for plots of pulse oximeter use across each of the 14 hospitals)
- Pulse oximeters were more likely to be used:
    - in some hospitals than in others
    - as time progressed through the study period of September 2013 to February 2016
    - when a Paediatric Admissions Record (PAR) was available to record admissions data and/or when a child[i]:
    - had a very high respiratory rate, indrawing, and/or was not alert
- After adjusting for case-mix and signs of illness severity, children with a pulse oximeter reading were significantly more likely to be prescribed oxygen than if they did not have a pulse oximeter reading, as were children who were:
    - in certain hospitals, and/or at later time periods
      and/or who had:
    - difficulty breathing, indrawing, cyanosis, and/or an asthma diagnosis
- Children with a pulse oximeter reading below 90% were more likely to be prescribed oxygen than children with a higher pulse oximeter reading.

The World Health Organization (WHO) and the Kenyan Basic Paediatric Protocols recommend using a 90% threshold for deciding when to give oxygen, so the above results suggest that these guidelines may be influential on HCW decision-making.

[i]Pulse oximeters were more likely to be used with children with a very high respiratory rate or with those who were not alert than in those without these symptoms, regardless of whether they had pneumonia or not; children with pneumonia were also more likely to obtain a pulse oximeter reading if they had indrawing than if they did not have indrawing.

[8] Seven other CIN hospitals were excluded from the analyses because pulse oximetry was used there with less than 20% of children on average between September 2013-February 2016 [see Section 3.5.2]; therefore, results may have been different if all 14 hospitals were included in the quantitative analyses.

6.1.2 Aims and approach of this qualitative research

I conducted this qualitative research to investigate explanations for the quantitative dataset analyses findings, and to explore the topic further, particularly concerning barriers to pulse oximeter use. (Sections 3.3.5, 4.2 and 4.6 contain information on the qualitative research aims and its fit with the quantitative research.)

The Research Questions:

1. Why might HCWs choose to use or not use pulse oximeters?

2. Why might HCWs not be able to use pulse oximeters even if they want to?

3. When pulse oximeters are used, how are they used? Are guidelines/recommendations followed?

To examine these, I directly observed healthcare delivery in three Kenyan hospitals, and conducted 30 interviews[9] with hospital-based healthcare professionals who provide frontline care to young children. This was a mix of doctors (five paediatricians, eight Medical Officers/Medical Officer Interns (MOs), and four Clinical Officers/Clinical Officer Interns (COs)) and nurses (n=10), who had varying amounts of experience, two Procurement Officials, and one Medical Superintendent. These individuals were based in 14 Kenyan hospitals that form the CIN (see Section 3.3.4), so sampling expanded beyond those hospitals of the quantitative analyses. (Chapter 4 explains the methods.)

[9] In this chapter I refer to all semi-structured interviews and semi-structured conversations (discussed in Section 4.6) as interviews and their participants as interviewees, for the sake of clarity; this is justified because the same topics were discussed in both modes of data collection (see Sections 4.6-4.7 for an explanation of the similarities/differences in the methods), and there were very few distinctions between views/experiences discussed in the semi-structured interviews vs. semi-structured conversations – the only exception (concerning barriers to oxygen provision) is discussed in Section 6.3.4

In this chapter I will explain how the Integrative Model of Behavioural Prediction helped frame the qualitative research findings; then I will discuss the findings within this framework; finally, I will present the HCWs' suggestions of how to increase pulse oximeter use in their wards.

6.1.3 Kenyan hospital admissions process

Typically, children will first undergo a brief assessment in an outpatient department, by a non-physician clinician; a pulse oximeter will rarely be available. The child may then be referred to the paediatric ward for a definitive assessment if admission may be needed. In the ward, typically a CO/COI[10] or MO/MOI carries out a full assessment, together with an admitting nurse. These are conducted largely independently, with separate medical and nurse note-taking. The full assessment may take place at a simple desk on the ward where the clinician/patient sit, or on larger wards in an 'admission room'. This process is typical of many low-income settings.

6.2 Interview transcript analysis

The Integrative Model of Behavioural Prediction (IMBP) [Fishbein&Yzer,2003; Fishbein&Ajzen,2010] is applicable to this research as it considers factors affecting an individual's intention to perform a behaviour; and how skills and environmental constraints might impact the individual's ability to perform the behaviour. (See Section 4.4)

The key factors in the model are:

[10] As described in Section 4.7.1, COs are non-physician clinicians: their training consists of a three-year medical diploma course and a one-year internship; they are more restricted in their practice than physician clinicians, but can be involved with many aspects of care such as diagnosing and treating patients, and can be specialized, in e.g. paediatrics, anaesthesia, dermatology, etc., carry out minor surgery, and run health centres. MOs are physician clinicians, who have not undergone postgraduate training to become consultants in, for example, pediatrics.[Mbindyo et.al.2013; Mullan&Frehywot,2007; English et.al.2004] HCWs of all of these roles are expected to use pulse oximeters, although it is the MOs/MOIs and COs/COIs who are most likely to be involved in the initial admissions assessment.

- Predisposing factors, e.g. demographics, attitudes, exposures to other interventions
- Factors influencing an individual's intention to perform a behaviour
    - Beliefs about the behaviour
    - Beliefs about what others think of the behaviour
    - Self-confidence
- Factors influencing an individual's ability to perform the behaviour once they intend to do so
    - Skills
    - Environmental constraints

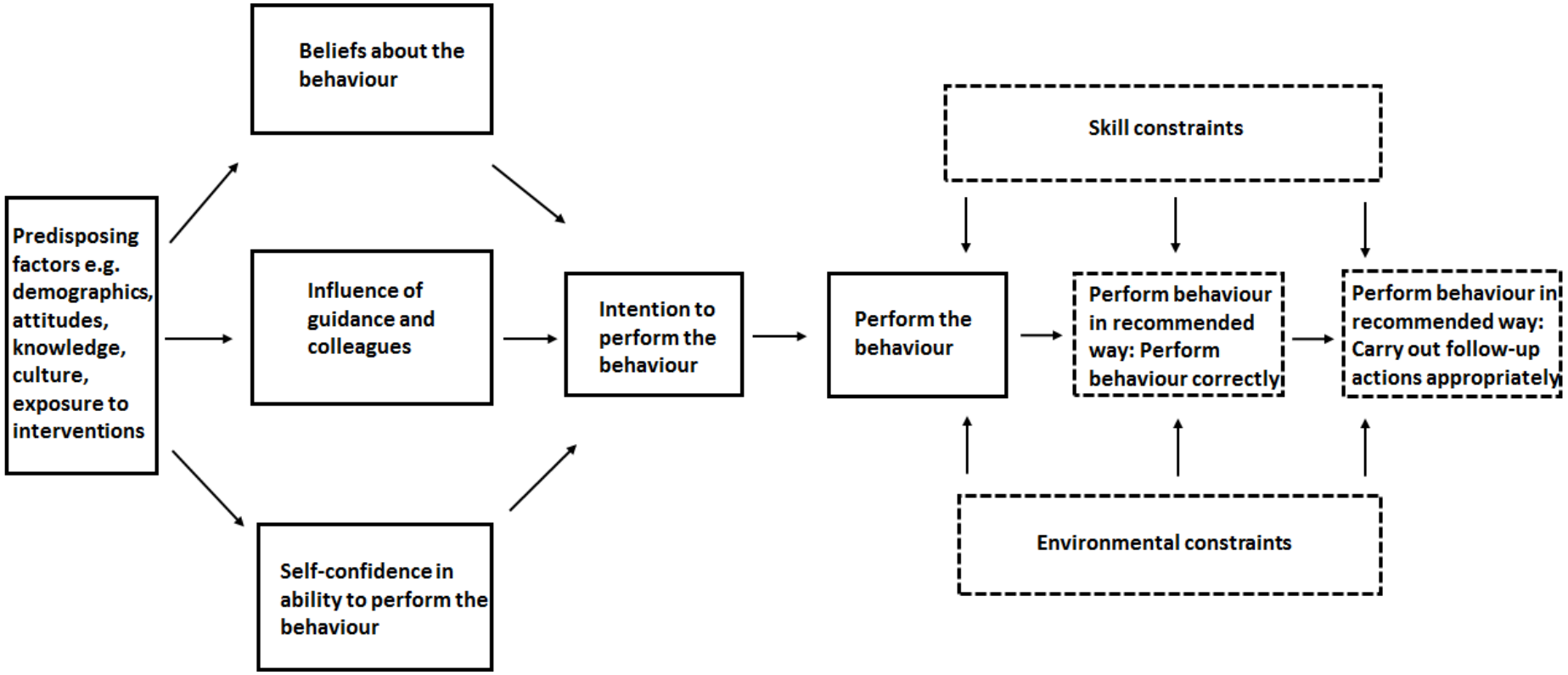
The main limitation of this framework was however revealed when it became evident from the data that *how* pulse oximeters are used, if they are used, is also crucial, but this is not included in the framework. To account for this variation in the way HCWs use pulse oximeters, I added an additional stage to the model (see Figure 6.1) which explores factors affecting how the individual performs the behaviour if they perform it, recognising that an individual's skills and environmental constraints are influential. It is not enough for HCWs to use pulse oximeters; to gain the full benefit, recommendations should be followed with appropriate follow-up actions.

Box 6.2 shows a summary of the findings, which are described in more detail within the IMBP framework in Section 6.3. Section 4.4 explains why the IMBP was chosen, and Figure 6.1b is the adapted model with each component found in the qualitative research.

Box 6.2: Summary of the findings, which are described in more detail in Section 6.3:

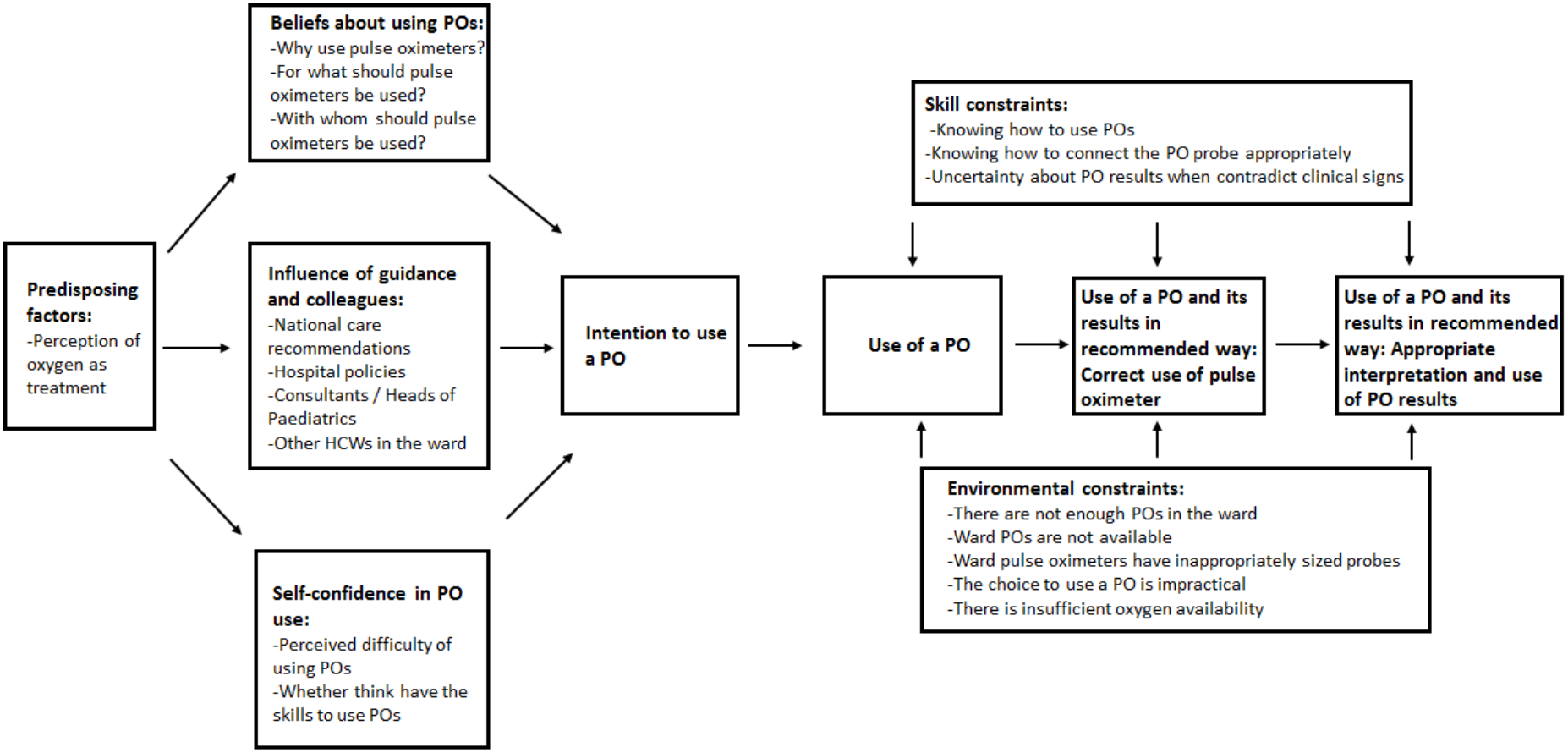
- There is a widespread belief amongst HCWs that pulse oximeters are important and useful.
- HCWs reported that pulse oximeters are particularly useful for guiding decisions of when to give oxygen, for helping to know when a child is improving or deteriorating, and for ensuring that oxygen is not over-used.
- If consultants/paediatricians are strict on pulse oximeter use, this can be a strong pressure/encouragement to regularly use pulse oximeters.
- Pulse oximeters are widely believed to be very easy to use.
- Many HCWs think that pulse oximeters should be used with all children at admission; others believe that certain children do not need a pulse oximeter reading, e.g. those without respiratory symptoms, or more specifically, those with e.g. diarrhoea, vomiting, or physical trauma. All interviewed HCWs intend to use pulse oximeters with at least certain groups of children at admission, if not with all.
- Almost all HCWs have experienced barriers to pulse oximeter use, often frequently.
- Lack of pulse oximeter availability was arguably the main barrier to pulse oximeter use discussed by the HCWs; this encompassed a lack of pulse oximeters owned by the ward (largely due to a lack of prioritization of pulse oximeters by the hospital/County, and a complicated and unclear procurement process), and unavailability of ward pulse oximeters for long periods of time once they break (due to inefficient repair processes).
- Other common barriers to pulse oximeter use include batteries running out (and taking a long time to be charged/replaced), not having appropriately sized probes, and HCWs not having sufficient knowledge of pulse oximeters to use them appropriately.
- An important barrier to appropriate pulse oximeter use is HCW uncertainty about how to interpret low pulse oximeter results; when HCWs (particularly those of higher seniority) see pulse oximeter results that contradict clinical findings, they may presume the pulse oximeter is malfunctioning and follow the indications of the clinical signs.
- When asked how HCWs within their ward could be encouraged to use pulse oximeters more often with children at admission, HCWs most commonly recommended a) obtaining more pulse oximeters, and b) providing training on how and why to use pulse oximeters.

Figure 6.1a: Diagram of the Integrative Model of Behavioural Prediction with the component that I added to reflect the findings of my work



Note: solid outline indicates components unchanged from the original model while dashes indicate components that I modified or added to reflect the findings of my work

Figure 6.1b: Diagram of the Integrative Model of Behavioural Prediction containing each of the factors found in the qualitative research



Note: PO refers to pulse oximeters; "uncertainty about PO results when contradict clinical signs" is considered a skills issue rather than a beliefs issue because it is a lack of skills/knowledge of how to interpret pulse oximeter results that has led to this doubt (see Section 6.3.3)

6.3 Research findings, framed within the Integrative Model of Behavioural Prediction

I will now describe the findings[11] (see Box 6.2), within the IMBP framework, under the following four areas:

- Predisposing factors (Section 6.3.1)
- Factors influencing HCWs' intention to use pulse oximeters (Section 6.3.2)
- The skill and environmental constraints influencing whether and how HCWs use pulse oximeters when they intend to do so (Section 6.3.3 and 6.3.4)

Figure 6.1 demonstrates the IMBP applied to the qualitative findings, and Table 6.3 lists each component's factors and sub-factors.

6.3.1 Predisposing factors

According to the IMBP, predisposing factors that may influence health technology use could include demographics, attitudes (e.g. concerning adopting new technologies in general), knowledge (e.g. of the relevant condition), exposure to other interventions (e.g. were other interventions successful, burdensome). This component was not as relevant for pulse oximetry in these Kenyan hospitals as other components of the model, but one predisposing factor was applicable.

Thus, HCWs' knowledge of and attitudes towards oxygen as a treatment are important in that these could influence how valuable they feel it would be to find a tool that guides the decision to

[11] In the quotes, () brackets are used for clarifications, indications of laughter, and ellipses to note cut text; {} brackets are used for words/phrases that are unclear; and [] brackets indicate the code number of the speaker, and whether they are a paediatrican (=P), Medical Officer / Medical Officer Intern (=MO), Clinical Officer / Clinical Officer Intern (=CO), or nurse (=N).

provide oxygen. Interview participants viewed oxygen as a particularly valuable resource, more so than other treatments. They emphasized that it is "*a life-saver*"[3;MO] and that "*we are lucky to have it*".[16;N] Several explained that children who need oxygen cannot go without; if oxygen is not available, a child who needs oxygen must be referred elsewhere. It therefore seems reasonable to think that these HCWs would be invested in learning about and using methods that facilitate and improve oxygen provision, e.g. pulse oximetry.

I had anticipated that HCWs' pre-defined roles could affect whether and how HCWs use pulse oximeters; for instance, if using pulse oximeters is generally the responsibility of, or has become a practice norm associated with, certain roles. However, according to the observations and interviews, while COs and MOs are those who usually use pulse oximeters to guide decision-making at admission, consultants/paediatricians or nurses who are responsible for a child's first assessment may also use them. Furthermore, following admission, all HCWs should have the opportunity to use pulse oximeters for monitoring. The pre-defined responsibilities of the HCWs' roles therefore do not dictate whether/how particular HCWs use pulse oximeters. It is worth pointing out that consultants (or MOs if the most senior clinician) are responsible for setting rules and expectations for these roles.

6.3.2 Factors influencing HCWs' intention to use a pulse oximeter

HCWs' intentions to use pulse oximeters can be influenced by their beliefs about pulse oximeters, their beliefs about how others value pulse oximeters, and whether they believe they are able to use pulse oximeters (their self-confidence in doing so) (Figure 6.1), each of which are discussed below in the context of the interviews. 'Beliefs' is an abstract term; for this research, beliefs are defined as the views and opinions of HCWs, i.e. what they perceive to be true, and how they feel about these subjective truths. Thus 'beliefs about using a pulse oximeter' refers to

what HCWs think are pulse oximeters' true characteristics and their opinions about these. Beliefs can be shaped by HCWs' prior experiences, their background, knowledge, attitudes, and values, the scientific evidence available, and what they perceive are the views of others.

a) Beliefs about using a pulse oximeter

The value placed on using pulse oximeters is affected by how HCWs think pulse oximetry contributes to decision-making, and which children they think would benefit from pulse oximetry. The HCWs commonly reported that pulse oximeters are **a very important tool** that should be used to help with clinical decision-making. It is necessary to make the subtle distinction between a perception of importance vs. usefulness, the former superficially encouraging HCWs to use pulse oximeters, while the latter being a deeper appreciation of pulse oximetry and understanding of *why* their use is important – a more powerful and sustainable impetus for use. Most HCWs believed that pulse oximeters are genuinely **useful**, because they help to deliver care, by improving care quality and/or facilitating their work. One CO presented a common view:

> "*I think they are so useful here, because we don't have any other tool of determining the oxygen saturation of the child or the patient. So we have to use it. We have to rely on that. We can't tell by sight.*"[14;CO]

Participants also reported that pulse oximeters are convenient, save time, and "*makes your work a bit easier*"[3;MO]. One interviewee added that if HCWs feel that using pulse oximeters benefits them and their work, they will be more likely to take care of them.

One interviewee suggested that experience in pulse oximetry determines perceptions of their importance and use, and thus future use; they explained that senior doctors know from experience that children with particular conditions need a pulse oximeter reading to determine if they require oxygen, and that without one, they might not receive oxygen. The interviewee therefore argued that, because they lack experience, interns are less likely to use pulse oximeters than more senior doctors. This assertion was however contradicted by a consultant

who, as described below, reported feeling more confident as a senior clinician to not use a pulse oximeter.

Several participants were less sure than others that pulse oximeters are useful. They questioned their reliability, stating that sometimes pulse oximeter results contradict clinical findings, which they took to mean the pulse oximeter was malfunctioning. This suspicion of pulse oximeter results was fairly common, although interestingly, it did not seem to affect HCWs' *intention* to use pulse oximeters; instead it affected how they interpreted the results. (See Section 6.3.3).

When discussing what HCWs perceived to be **the roles of pulse oximeters** in assisting with clinical decision-making, HCWs widely reported that pulse oximeters are "*a tool that helps you to determine which patients require oxygen and which ones don't require oxygen*"[3;MO], and also described other indications for pulse oximetry – shown in Table 6.1.

Others reported that not only are pulse oximeters useful for guiding oxygen provision, but also when to take a child off oxygen, as oxygen is frequently over-used (when available). Oxygen overuse can be particularly problematic as oxygen "*is expensive, especially in our setup. We need to really use it cost-effectively*"[2;P]. Using pulse oximeters can therefore save hospitals money by avoiding inappropriate oxygen use. An interviewee added that this can also lead to shorter ward stays and thus possibly less hospital-acquired infections.

Table 6.1: Indications for using pulse oximeters mentioned by HCWs, other than to determine which children need oxygen

Role of pulse oximeters	**Quotes**
Show that something is wrong	"*The pulse oximeter, they guide us on how the saturation of the oxygen is in the blood, and in the tissues. So, when it is low, it means there is something somewhere which is not right.*"[16;N]
Help to decide how much oxygen to give	"*It gives me an idea about when the patient came, the SpO2 was 80 without oxygen, and once I put oxygen I need to know, I am going to a level that I need.(…) With my experience you find, with an SpO2 monitor you can really titrate your oxygen; it can assist you, to titrate and give the minimum you need*."[2;P]

Indicate whether a child is improving or deteriorating	"*With subsequent reviews and follow-up, I can still use my SpO2 assessment to decide whether the patient is improving or not improving.*"[2;P] "*Even as a baseline. Cuz anything can happen, over the stay of admission, and you do have to know, to have a baseline there, of how they came.*"[12;MO]
Aid diagnosis	"*Apart from just telling us about who needs and who does not need oxygen, there are patients who will fit the criteria for certain diagnosis, just because of the pulse oximeter*."[8;CO] "*Mortality's reduced, even with a, the pulse oximeter, cuz it makes a diagnosis quicker and you know what you are dealing with.*"[9;MO]
Assist with dealing with uncertainty	"*Cuz {lots of/those} time that you'll guess a baby needs oxygen or doesn't need, then those are the time pulse oximetry just makes your work easier.*"[9;MO] *"Ideally, {what is here} child in distress, and you get a low SpO2, it really helps you in making a quick decision that this child will need oxygen.*"[12;MO]
Aid in assessing the illness severity	"*It determines the severity, of maybe any respiratory condition.*"[4;CO]

HCWs had varied views on whether pulse oximeters inform the decision to prescribe antibiotics, with some reporting that pulse oximetry has no effect on antibiotic provision or at least not alone, while others reported that "*it guides you on the diagnosis and that diagnosis actually will lead you to decide whether you are giving antibiotics.(…) So it's a, it's a guiding indicator*"[9;MO] or "*I think, what we do then, with the vitals, which SpO2 is part of the vitals, just to see(…) if you are improving or not improving, yeah. So, it can affect your change of antibiotics or treatment."*[4;CO] One interviewee noted that pulse oximeters indirectly influence antibiotic provision by helping classify illness severity. Another agreed, adding that pulse oximeter readings can be cut-offs for deciding treatments e.g. oral vs. injectable antibiotics. This reflects partial acceptance of existing guidelines where pulse oximeter use is clearly linked to antibiotic use.[Kenyan MoH,2016]

The WHO's Oxygen Therapy for Children guidelines specify that "*Pulse oximetry should be used to monitor all children at the time of admission (not just those with pneumonia)*". Accordingly,

the Kenyan Basic Paediatric Protocols, which draw heavily on WHO recommendations, and which are widely used in Kenyan hospitals, state that oxygen saturation should be checked as part of all children's initial assessment prior to a full history and examination. When HCWs discussed their views on **with whom pulse oximeters should be used**, many interviewees agreed with the guidelines and wanted to use pulse oximeters with all children at admission, regardless of their condition; some were adamant in their assertions that this is important. However, others said they choose to use pulse oximeters with specific children at admission. The most commonly mentioned groups were those with suspected respiratory conditions (particularly pneumonia), those with cardiac issues, children who are not alert, and children with clinical signs such as high respiratory rate and difficulty breathing. (See Box 6.3) (Note: these are the children who HCWs consider requiring pulse oximetry, not necessarily those with whom they use pulse oximeters).

Box 6.3: children with whom HCWs intend to use pulse oximeters, if not with all

The most commonly mentioned characteristics

- Suspected diagnoses/conditions
    - Respiratory conditions (broadly defined)
    - Pneumonia
    - Asthma
    - Cardiac issues
- Symptoms and clinical signs
    - High respiratory rate
    - Difficulty breathing
    - Children who are not alert / are unconscious
- Demographics
    - Younger children, e.g. neonates, aged 0-2, under-fives

Other characteristics mentioned

- Suspected diagnoses/conditions
    - TB
    - Bronchiolitis
    - Diabetic ketoacidosis
    - Metabolic acidosis
- Symptoms and clinical signs
    - Cyanosis
    - Convulsions
    - Indrawing

Note: these are the children who HCWs consider requiring pulse oximeter readings, not necessarily those with whom they actually use pulse oximeters

Accordingly, when HCWs were asked which children they thought did not need pulse oximetry, all who said all children need pulse oximeters also said there were no groups of children who do not require a pulse oximeter reading. Others listed various "*children who don't need pulse oximeters*"[8;CO] and so for whom "*doing an SpO2 doesn't really make sense*"[3;MO], particularly children without respiratory symptoms or cardiac symptoms, or more specifically, those with diarrhoea, vomiting, dehydration, malnutrition, an abscess/sepsis, a cut, history of a fall, or other physical trauma. (Section 7.2 compares these results with the quantitative

findings). Interestingly, a nurse said that when there are obvious signs of oxygen need, e.g. indrawing or difficulty breathing, they would put the child straight on oxygen without using a pulse oximeter. Also, a paediatrician reported that while they think pulse oximeters should be used with all children at admission, and they advise junior doctors this, they themselves generally choose to only use pulse oximeters with children who appear particularly sick or unstable.

b) Influence of guidance and clinical colleagues

HCWs frequently mentioned that national/international **guidelines**, particularly the Kenyan Basic Paediatric Protocols, help direct their diagnosing and treating; they appeared to consider the Kenyan Basic Paediatric Protocols as important and useful. Accordingly, an interviewee said that these guidelines are responsible for pulse oximetry uptake in their hospital. Furthermore, a HCW reported that CIN assessments of hospital care adherence to external recommendations sometimes led to competition between hospitals, resulting in increased efforts to use pulse oximeters.

> "*Basically we keep on assessing ourselves, and measuring ourselves against {} and how we are performing. And because of that, we tend to push each other to do better, each time we have an assessment.*"[3;MO]

HCWs' decisions on whether to use pulse oximeters may also be influenced by **their hospital's focus** (or lack thereof) on pulse oximetry. Thus, a HCW argued that variability in pulse oximeter use across hospitals may be because "*some hospitals might think it's (a pulse oximeter's) not useful, others might put emphasis on it*."[12;MO] Several HCWs discussed how their hospital's form for recording admissions data affected their pulse oximeter use. For instance, the Paediatric Admission Record (PAR), a widely used and recommended form, has a box for oxygen saturation. HCWs felt that having this place to record the reading reinforces that you should use pulse oximeters, and reminds you to do so.

> "*If daily routine charts says you start with SpO2, you go to temperature, you go to pulse, you see? They have to fill. To fill everywhere. So, you are encouraging them to continue doing that*."[15;N]
>
> *"You may miss something then probably it guides you on what to ask, or other examination. Then there is a place where you have to give the oxygen saturation. Then you put that."*[11;CO]

Again, these results complement the quantitative findings – see Sections 5.5.2 and 7.2. One interviewee said this pressure can lead to interns falsely reporting they have used pulse oximeters. Some forms do not have a space to record pulse oximeter readings and so do not promote pulse oximetry.

The consultants' views of pulse oximeters (or those of MOs when the most senior clinicians in the ward) also influence HCWs' clinical behaviour. Some HCWs explained that their consultants "*really insist on the importance"*[11;CO] of using pulse oximeters, and "*every day they ask, how much was the pulse oximetry."*[9;MO] The result is that "*It's like a chain, yeah; the consultant ask me, and me I ask the intern, how come you didn't do this. So it becomes like a norm or a culture, like everyone has to do SpO2 for every baby.*"[9;MO] One interviewee suggested that when paediatricians are away from the ward, removing this influence, pulse oximeter rates decrease. Interviewees argued that *"in some hospital they might not use it (*pulse oximeters*) cuz you find that probably, the Head of Department, of Pediatric, is not strict on the use*"[9;MO], and if consultants do not request pulse oximeter readings, HCWs may feel there is no point in taking them.

> *"Also the consultants, who are in charge of everyone else; if it has become a trend that they ask what is the SpO2, cuz even them sometimes they won't, so there's no need, why would you give {}. It happens from, it happens from the top."*[8;CO]

Finally, **the beliefs of other HCWs in the ward** concerning pulse oximeters may influence a HCW's intention to use pulse oximeters. Some HCWs thought that pulse oximeter use is variable in their ward:

> "*Some take it, some don't, it depends with the condition of the child sometimes(…) On admission sometimes you find it is taken, sometimes it's not, so you have to do it yourself.*"[14;CO]

Similarly, one interviewee said they thought roughly half of children in their ward obtain a pulse oximeter reading at admission, and that this drops substantially when there are barriers to use. However, many HCWs thought their colleagues widely use pulse oximeters:

> "*Actually, pulse oximetry use, you know, this is good, I must say.*"[2;P]

> "*From what I've seen from my colleagues, when we admit, we always use it. If it's there, we'll use it.*"[12;MO]

> "*To every file, if I open this or this, I'll see pulse oximetry readings somewhere. Any of these files you taking, they'll be there.(…) From the amount I have been in here(…) I've just seen SpO2 being taken*."[4;CO]

In wards where HCWs see others consistently using pulse oximeters, they can start to feel there is a pervasive "*perception that you're meant to take the SpO2*"[3;MO]. This was particularly important for interns. Thus, several HCWs reported that when interns first arrive in the ward they do not regularly use pulse oximeters; however, soon they see it is the norm to do so and over time get accustomed to this system.

> *"Every time there's a change in the people in the department, if they find people have been using this, then they'll have to, to adjust.(…) If you come and then it's a routine, everyone is doing it, then it should, it should, it should trickle down to everyone else."*[8;CO]

Once pulse oximeter use becomes the norm, "*then also it will just be a tool that we use to, for routine admissions, for routine, as a routine.*"[8;CO] This can protect against possible change in practice associated with frequent HCW rotations.

Interestingly, HCWs from the same ward did not necessarily agree on whether pulse oximeters are widely used within their ward. It is therefore their *perceptions* of others' beliefs and behaviours that HCWs are describing (rather than objective descriptions), and it is these perceptions (whether reflected in reality or not) that influence their intentions.

c) Self-confidence in ability to use pulse oximeters

A HCW's self-confidence in their ability to use pulse oximeters depends on how difficult HCWs consider pulse oximeters are to use, and whether they perceive that they have the skills to use them. If HCWs do not have self-confidence in their ability to use pulse oximeters, they may not want to try to use one.

Generally, HCWs were first taught about pulse oximeters at medical school. However, they were mostly taught basic theory rather than practising using them, learning about their importance, or how to interpret their results.

> "*You know, they don't have them in the schools but in the hospitals you go, we're told how to connect them, how to use them, and how to assess the child.(…) We learnt in school, when we were in training; not really in training, because most of the time it's theory. Now when you go to the hospital, you have to learn to use it.*"[14;CO]

When HCWs arrive in the paediatric ward, nurses or consultants might show them how to use pulse oximeters; often they are left to pick up the skills by watching others. In general, HCWs reported that no formal pulse oximeter training had been provided since they arrived in the ward.

> "*I never used to understand how they work but I remember we, we put it on a finger, and it gives you a reading. That was {what we basically studied}.(…) I don't think I've ever been trained on pulse oximeters, ever since then.*"[8;CO]

The few exceptions were following pulse oximeter donations. In one situation, this was internal training, not donor-provided, while in another, several staff were trained after the donation and these staff trained the others. Interestingly, these descriptions were not necessarily corroborated by others in the same ward. But generally training was not provided even following donations.

> "*When they come, they have their manuals and there's no one who comes and trains the staff on how to use them.(…) I think, we staff, we haven't been trained on how to use these machines because, I think the models are different. Companies are different. They are, ok, as much as they are digital, they are just not very automatic*."[10;N]

Many spoke of the importance of periodic (not one-off) training for all HCWs:

> "*It is needed, it is needed. It's actually needed for, all clinicians should be trained on pulse oximetry, the importance, the interpretation, the use.*"[2;P]

> "*Learning is a process, we have to learn from different people, so we are taught how to use it here. Because sometimes you find it is a different machine from which you used.(…) The machine, they are not all the same; maybe the make is different, the way it is made, and the other one is different. Yeah. For the portable is different from these other ones, so you have to learn {new}.(…) You have to keep learning. Yeah. It's good to have the trainings, it's good for us. Because at times you might forget what you have to do. Yeah. It's easy to forget, but you have to learn in a different way.*"[14;CO]

Perhaps because of insufficient training, a few HCWs thought that some types of pulse oximeters can be challenging to use, or that pulse oximeters can be difficult to use in certain situations:

> *"Not so easy – if the machine is working well it's easier, but when it's troubling you, you have to struggle a little*."[14;CO]

However, nearly every HCW thought pulse oximeters are easy to use. They said "*it's just switching it on and fixing it*"[2;P], and "*for me I don't think it's a problem*."[9;MO] Some added the caveat that pulse oximeters are easy to use but only once you are shown how, while others stated "*it's so easy, I don't think that you need to have formal training to use one*"[11;CO]. Another common comment was that pulse oximeters produce results very quickly: "*we just apply, immediately it will tell you.*"[15;N]. So, almost all HCWs reported that they have the skills to use pulse oximeters.

> *"I don't have any problem in using them.(…) On the job, you are trained, and you just, you can even see how it is used, and you will also do it, and, you know, because it's not a complicated thing, it's a simple thing.*"[15;N]

This perception that pulse oximeters are easy to use may have been one of the reasons why more formal training was not provided – it may have been assumed that HCWs could just acquire the skills by watching others. However, there is a risk that insufficient formal training might undermine not only HCWs' self-confidence in using pulse oximeters and therefore their intention to do so, but also (sometimes without their realising) HCWs' ability to use and interpret pulse oximeters appropriately if they attempt to use them. (See Table 6.2).

6.3.3 Skill constraints limiting HCWs' ability to use a pulse oximeter appropriately when they intend to use one

Thus, even if a HCW intends to use a pulse oximeter, insufficient skills (due to insufficient formal training on why, when and how to use pulse oximeters and interpret their results), can prevent the HCW from being capable of using the pulse oximeter appropriately. Hence, a HCW who has not been sufficiently trained in pulse oximeter use might a) not be able to obtain a reading when they try to use a pulse oximeter; b) obtain a pulse oximeter reading that they do not realise is inaccurate; and/or c) misinterpret pulse oximeter results. (See Table 6.2)

HCWs had variable views on whether others in the ward have difficulty in using pulse oximeters. When HCWs acknowledged that others do not/might not fully understand how to use pulse oximeters, they said this might occur for all HCW cadres, including nurses, COs, MOs, and some even said consultants. Several HCWs noted that other HCWs in their ward do not know how to **place pulse oximeter probes correctly**:

> "*At times, you find that you ask maybe the sister, like put this baby on pulse oximetry, we see at how much the baby is saturating, but you find that they do not know even how to connect, and you come back you find that the pulse oximeter has been connected but it's not reading, but you put it in the right position, then it starts reading*."[9;MO]

> "*When you don't put the probe correctly, it will give you a different reading.(…) There are people who will not really place it correctly and it gives you a different reading, or it doesn't read at all, then you think the baby is really desaturated, but when you come with a different pulse oximeter, and put it correctly, it gives you a proper reading.*"[1;MO]

However, there are also situations in which a HCW obtains an accurate reading but does not interpret or respond to it appropriately, leading to an unsuccessful use of the pulse oximeter. One example of how results can be misinterpreted was highlighted by a HCW who consistently confused oxygen saturation with pulse rate during the interview. A more common issue however, is, as discussed below, HCWs' uncertainty concerning pulse oximeter results when these contradict the child's clinical signs.

The WHO Oxygen Therapy for Children guidelines and the Kenyan Basic Paediatric Protocols recommend that a child with a pulse oximeter reading below 90% should be given oxygen. All but one interviewee said this is the threshold they use in deciding whether to give oxygen. They said "*If it's below 90, obviously we administer oxygen.*"[5;N], and "*That is the standard*" because that is "*Our guide from the Ministry"* [3;MO]

When HCWs were asked more specifically about whether they give oxygen to a child who has particular pulse oximeter readings, they did not necessarily adhere to this threshold. A few said they never give oxygen when a reading is above 90%, "*because it's not needed*"[15;N] and *"they can't have distress when their oxygen saturation is so high*."[14;CO] But many said they still provide oxygen when a reading is higher than 90%, if the symptoms indicate the child may need oxygen. The most common symptoms HCWs listed as signs that children might need oxygen, even if they have a high pulse oximeter reading, were difficulty breathing, high respiratory rate, or, described more generally, respiratory distress. Other symptoms listed included cyanosis, grunting, and indrawing. Symptoms also mentioned but rarely were gasping, stridor, wheeze, convulsions, pallor and head nodding. Although similar, these were not necessarily the same symptoms HCWs listed as indicators of oxygen need in general, listed in Box 6.8.

A particularly problematic barrier to effective pulse oximeter use found through these analyses, was **HCWs' uncertainty about low pulse oximeter readings**. Many HCWs explained that when a pulse oximeter reading is below 90% (and so the WHO and Kenyan Basic Paediatric Protocols would recommend oxygen provision), but the child does not also have clinical signs indicating they need oxygen, they conclude that the pulse oximeter is malfunctioning and therefore prioritise and trust the clinical signs over the pulse oximeter results and do not give oxygen. Over time with further experiences of pulse oximeters contradicting clinical findings, they come to view pulse oximeters as unreliable and are even less likely to trust them. Thus, children who need oxygen might not obtain it, even if a pulse oximeter is used. This is supported by the

quantitative findings which indicate that many children with low pulse oximeter values were not prescribed oxygen – see Sections 5.2 and 7.2.

While some studies suggest pulse oximeters are less accurate with certain children (e.g. those with carbon monoxide poisoning or hypothermia/vasoconstriction, or due to excessive movement (e.g. from shivering, convulsions, agitation), nail polish, dirty sensors, and at readings below 70%.[Jensen et.al.1998; Blaisdell et.al.2000; Chan et.al.2013; Langley&Cunningham,2016; Olive,2016; WHO,2011b]), only two interviewees mentioned these groups. Other HCWs reported that they were concerned that pulse oximeters might be malfunctioning when their results contradict clinical findings.

There are many situations in which a child may need oxygen (as shown by low oxygen saturation) but the HCW may not see symptoms of this.[Hanning&Alexander-Williams,1995; Ayieko&English,2006] Accordingly, studies show pulse oximeters can identify 20-30% more children with hypoxemia than by using clinical signs alone.[WHO,2014b] So it is these children for whom pulse oximeters are most important, as they would not be given oxygen if only clinical signs were used. However, many HCWs were not aware that children could have hypoxemia without clinical signs indicating this.

HCWs' doubting of pulse oximeter results that contradict clinical findings is likely to again be due to insufficient training on how pulse oximeters function and how to interpret their findings (see Section 6.3.2 and Table 6.2). HCWs' perception that pulse oximeters are malfunctioning, and are low quality and unreliable, may stem from experiences of pulse oximeters breaking (or being used incorrectly so they appear broken). Box 6.4 contains several quotes illustrating HCWs' lack of confidence when low readings contradict clinical signs.

Box 6.4: A selection of quotes illustrating HCWs' uncertainty about pulse oximeters when their low readings contradict clinical signs

HCWs' perception of pulse oximeters as unreliable as a result of their results contradicting clinical signs:

"*At times we tend not to believe them cuz some of these machines we use are from China so they give you different readings at times.*"[MOI;1.1]

"*In some ways they are useful, in others they aren't. Because, a child can come, they are completely stable. No difficulty in breathing, respiratory rate is ok, but when you put the SpO2 machine, it shows you the child is at 80%, but when you look at the child clinical, ah you don't think they should be on oxygen. So that's one let down."*[MOI;6.1]

"*I don't think they are so reliable, even the, cuz sometimes they'll give you an SpO2 of 80, and the pulse rate is 30, it doesn't make sense, some of the time. So I think it's a useful tool, but it also depends on the machine you have, if it's working well.*"[MOI;1.2]

The frequency of this occurrence:

"*It's quite often. It's really often. Like, I have 3 children already in acute* (room) *1 whom their pulse oximeter and their clinical picture are totally different. Yes. So it happens a lot.*"[MOI;6.1]

Many HCWs resolve to always look at clinical signs as well, so they can validate the pulse oximeter results:

"*Anyone who is saturating at room air less than 90% is a person we will consider for oxygen, but we'll also monitor the respiratory rate to confirm that, if this corresponding to the SpO2 machine*."[8;CO]

"*Well, I think they are useful, but sometimes there's a discrepancy, on the results they give us. Cuz at times you can find that it's, it has a low reading, and when you look at the child, clinically they are ok. And so it also depends on what, which type you are using.[…] Yeah, so we actually use both of them, both the clinical, clinical evaluation, and the SpO2 readings.*"[1;MO]

"*They will be reliable, but I still think you need to correlate the clinical findings. Yeah. Because in some cases, it does help, like actually you can see the baby's really bad, and it's correlating with the oximeter findings; but in some, this does not correlate. So I still think we have to use concurrently, yeah; we just cannot rely on one.*"[1;MO]

Only two interviewees pointed out accurate examples of when pulse oximeters may be less accurate:

"*There's things that can make an SpO2 have false positives or false negatives or such, it can happen, especially if the patient is in shock, or is hypothermic, or the patient is having anaemia*. *Ok the anaemia, so there are some, you'll, I might not entirely rely on the SpO2 machine, to make the decision of whether to give oxygen*."[2;P]

"*From what I've seen, a child may have, cold peripheries, and [when] it's cold, I don't know, the SpO2 machine reads it really low. Other than that I don't know what causes it."*[MOI;6.1]

Interestingly, paediatricians and MOs were more likely than COs to describe being concerned when low pulse oximeter results contradict clinical signs, and nurses were least likely. It is therefore those with more medical training/seniority who have the confidence to question the technology and its guidelines.

Not all HCWs automatically rely on clinical signs if they doubt pulse oximeter results, and some attempt to check if the pulse oximeter is really malfunctioning:

> "*In case I doubt, then I will, if I have another one I will try to check with another one, if not so, then I will, what I will do is I will do it on myself and other people around, just to confirm whether it is working or not.(…) If then I'm still confused, I might need to go back, and examine the patient again, take another history, do another examination, and make another, decide whether I really need to give*."[2;P]

> "*Not all the babies we put on oxygen. Maybe you have to repeat again. Because the machines here, maybe it's not working well, so it depends on the baby*."[14;CO]

Some HCWs unconditionally trust pulse oximeter results:

> "*I'd say, just trust the reading, cuz you don't have any other options*."[14;CO]

Table 6.2: How insufficient training can influence pulse oximeter use in a myriad of ways

Topic of insufficient training, concerning pulse oximeters	**Potential consequence for a HCWs' intentions and behaviours**
Their importance / usefulness	A HCW may not see the point in using a pulse oximeter and so may not use one
When to use them	A HCW may not use a pulse oximeter with the appropriate children
How to use them	-A HCW may not feel they have the self-confidence to use pulse oximeters and so may not try -A HCW may not be able to obtain a reading when they try to use a pulse oximeter -A HCW may still use a pulse oximeter without knowing the appropriate way, and may therefore obtain an inaccurate result. If they do not realise that the result is inaccurate, they may make inappropriate treatment/care decisions in response to the result
Their limitations	A HCW may incorrectly presume that pulse oximeters are not as accurate in certain situations and therefore not trust the results in those situations

How to interpret their results	A HCW may misinterpret a pulse oximeter's results, e.g. mistrusting low readings that contradict clinical signs

6.3.4 Environmental constraints limiting HCWs' ability to use a pulse oximeter appropriately when they intend to use one

A range of environmental constraints may also prevent HCWs from using pulse oximeters with any/some children, or may lead HCWs to incorrectly use pulse oximeters or inappropriately interpret their results. Thus, as one MO stated:

> "*There are situations when you want to use it* (a pulse oximeter) *but you can't use it, due to things you can't control, things {} that are not under your control.*"[3;MO]

One such constraint concerned pulse oximeter **procurement**. Thus, all but three interviewees reported that their ward does not have enough pulse oximeters.

> "*No, no, no, no, it's not enough, it's not enough*."[1;MO]
>
> "*Also sometimes you are doing a ward round, and that one SpO2 is with another person, taking an SpO2 on another child; we have many admissions, so it's usually on demand.*"[2;P]
>
> *"The pulse oximeters here are very useful. The problem is they are very few.(…) We always need, it's, there's always one person who needs it but you're using it, so it happens every time, it happens all the, every day."*[8;CO]

When the research was conducted, each paediatric ward had 0-4 pulse oximeters. HCWs thought that 2-15 were necessary. Many thought it would help to have one pulse oximeter in each ward room, of which there were up to seven. Interestingly, when HCWs were asked how many pulse oximeters their ward currently had, they did not necessarily state the same number as other HCWs within the same ward (and some even contradicted themselves within the interview). This confusion may be because HCWs are accustomed to not having access to one/multiple ward pulse oximeters (reasons are described below) so they do not know their ward's total number of pulse oximeters.

Sometimes doctors bought their own pulse oximeters because of shortages. Occasionally this helped stop-gap supply issues:

> "*Even doctors, I told you?, they have, they've bought, they bought, they have them in their pockets; so {note} that, sometimes, the hospital ones, maybe, they are not in order, but you cannot {lose/use} pulse oximeter, as long as even doctors are around, they have.*"[15;N]

However, relying on doctors' personal pulse oximeters is not sustainable. As one HCW stated:

> "*It's only us clinicians, at times if you have your own, but it gets lost, or it also becomes faulty, and it's quite expensive so you cannot buy; you only buy once and it gets faulty; that's it. You're like, I will not incur cost of buying another one, you see*."[9;MO]

HCWs recognized that a key reason for hospitals not providing enough pulse oximeters is that they have limited resources to buy new equipment. However, the procurement process itself was more widely criticised, for taking a long time and lacking transparency.

> "*Because pulse oximetry I know it's an essential equipment to have, but we've never had it. Even this ones we have, they came just a few months ago. Cuz the County had not bought any for the hospital*."[9;MO]

> "*It can take months to years to get new equipment after a requisition for it.*"[2;P]

> "*Oh, I think, it takes forever, that's what I'm told, it takes forever.(…) I wanted paper to print. It's taken me 6 weeks to finally get printing papers that I wanted, and it was a project that I wanted for 6 weeks ago. So you can imagine, there's never time, you want something immediately and get it immediately.(…) If you want something, to go from here to get to the process of going somewhere, going and getting it from a shop, or getting it from, and bringing it back here, it's {let's say 3 months}, I think, that's, that's the estimate.*"[8;CO]

HCWs complained that the County, which is often responsible for procurement decisions, does not prioritize pulse oximeters, so does not purchase them when requested, and that it is hard to convince these officials of pulse oximeters' importance because they are not HCWs. One HCW claimed the County often makes procurement decisions based on suppliers it has relationships with rather than on hospital needs; consequently, several times that HCW has received something different than they requested, and that is unneeded. Others said 'Procurement' is not sure about obtaining more pulse oximeters because they think they will be mishandled or

misplaced. Furthermore, HCWs frequently referred, frustrated, to procurement as a "*whole process*", and sometimes made resigned comments like "*This is government*"[3;MO].

HCWs' procurement process descriptions were often long and complicated, while many HCWs said they do not know how the process works. Moreover, while the process likely differs by hospital, and so one would expect HCWs in different hospitals to describe the process differently, in the interviews HCWs often described the process differently than other HCWs working within the same ward. Furthermore, while only one Medical Superintendent and two Procurement Officials from two hospitals were interviewed, and so I cannot make definitive conclusions based on their interviews, or know if the procurement processes they describe are similar at other hospitals, it is notable that the Medical Superintendent and Procurement Officials described a different process than the HCWs, including differing on who they reported is responsible for procurement decision-making.(Box 6.5 has examples of how HCWs, the Medical Superintendent and Procurement Officials described the process.)

Box 6.5: examples of HCW descriptions of the procurement process, and the explanation given by the Medical Superintendent and Procurement Officials

HCWs' descriptions:

- "*We just report it to the In Charge of the ward; then the In Charge of the ward talks to the Nursing Officer in charge of the hospital, and then they discuss with the budgetary committee on how it can be bought.*"[16;N]
- "*It's through administration, and there must be, they must have, seated down, sittings, to plan for that. We raise concerns of what we don't have; we sometimes even put down a list, at the beginning of the year, we put a list of what we need, according to priority. And then, we just see them buying for us, as time goes. You ask for this, you are given. But, if there's an urgent need, maybe a machine has broken down, that one, it can be bought as an emergency, through, in Nursing Department, through my Nursing Officer in Charge, or just channel that way, and it will reach the Medical Officer, and it will be bought. Some of them may not be bought immediately, but they plan for it and you still get.*"[15;N]
- "*I know that that takes a process, that is a process. Cuz you have to involve the County, we have counties in Kenya, you have to {look/work} counties before you purchase, because, for example, the money we, the patients, probably raised the money we have here is {come}, so you need to buy any equipment you have to take it through the hospital committee, then {till} they take it, they {upgrading} and take it the County. Yeah, so it's not a short process.*"[11;CO]

- "*If there's something that you need, most of the time we tell the, we have In Charges, the Nurse in Charge, we let them know what we need, then they go to the higher authority. Yes. Then you have to write a letter, and ask for what you want; that goes to the, I think to the Medical Superintendent; then they have to work with the, the people who supply. Yeah. But I'm not sure what goes on in between. (*Laughs*). Yes. But all, when we need something, we talk to the In Charge.*"[1;MO]
- "*If a new one is needed, we write a requisition, we call it a requisition order, which is taken to the Medical Superintendent's office; the Medical Superintendent has to sign for its procure, for its purchase; once he signs, then it has to go to the Procurement department, which now organises to have them delivered, by whoever has been given them, {and they} to deliver.*[2;P]
- "*That is always done by the ward managers. They order it through the store manager and we, and to the hospital administrator. Yeah, then the {} administrator will get into the procurement procedures of acquiring one." ; "It also depends with what should be purchased. There are equipment that will take long to be purchased, there are things that you will get instantly. So it always depends with the, I think {cuz there are} cost implications of everything that you want. And use. Yeah.(…) The things that do not need a lot of financial implications. Then you can get them {quickly}. But anything that needs more financial support, then sometimes it may take some days*."[5;N]
- "*It's usually a long process, cuz you have to write a proposal first, why you need it; after that it has to go to the Finance Department, first you have to write to the Chief Officer, then you take it to the Finance Department; the Finance Department through the Chief Officer, they have to approve, for the funds to be available; then they are going to procure that equipment and it will be brought. So it's quite a long chain, it's not something, like for me, I have to write a proposal, maybe to the Head of Department; the Head of Department write another proposal, maybe to the HO, that is the Head of Administration; that one writes requesting to the County finance and the Chief Officer, they approve*."[9;MO]

Steps described by Medical Superintendent and Procurement Officials:

- After devolution was instigated, the County was initially responsible for deciding which procurement requests to approve, but this is no longer the case
- During the current process, the County provides funding to the hospital; the Medical Superintendent can choose how to allocate this funding
- The Medical Superintendent receives an equipment request from e.g. the Nurse in Charge
- The Medical Superintendent decides whether to approve the request (if the equipment is very expensive then the County might need to approve it)
- If they approve, then Procurement (within the hospital) asks for quotes from suppliers for the equipment
- One of the suppliers is chosen, the equipment is bought, and is delivered to the ward
- This process can take a few days or weeks, or longer, depending on e.g. the equipment's cost and whether they already have a relevant supplier

Some HCWs said the procurement process is straightforward and efficient and that they receive requested equipment, but this was not the view and experience of the majority. There seems to be substantial confusion surrounding the procurement process, e.g. the steps and who is responsible for different stages and decisions. This confusion suggests, either the process is not

being performed as intended, and/or that HCWs do not accurately understand the process. In their role as mid-level managers, senior clinicians may also be reluctant to engage in management, resulting in a wilful ignorance of procurement.[Nzinga et.al.2013]

There were mixed views on whether devolution[12] helped or hindered the procurement process. Some were frustrated that they no longer had someone in the hospital with whom to discuss procurement. An interviewee thought it was better before devolution when a hospital committee would decide budget allocation amongst the hospital departments, based on departmental proposals, and then departments could decide how to spend this funding. Another said devolution has led to many strikes over pay and working conditions -- which clearly impacts care. Several HCWs argued that procurement takes longer after devolution, while others disagreed. It was not however within this research's scope to examine devolution's impact on the healthcare systems and hospital policies.

Donors play a key role in equipment supply. Some viewed donations favourably, referring to donors as "*partners*"[15;N] and that "*They really helped us.*"[6;N]. Another HCW claimed donations speed up procurement: "*It's a long process,(…) it's easier if you can get donors*".[9;MO] However, one HCW was concerned with the 'donor mentality':

> "*Most of the times we realize, hospitals in our country, even these pulse oximeters we get, they're usually from donors. I don't know why, they're not so expensive, I don't know why we can't buy them for ourselves. It's a donor mentality. It's sad.(…) This is a personal opinion: we don't need to rely on donors to get some of this {}. They're basically how much? They're like 50, like $25. For $25 you {could} buy a pulse oximeter. It's like 2,500 Shillings {in Kenya}. But you see we, {governor} goes to beg people to provide certain basic things which, are really affordable*."[3;MO]

Another said the County initially approved their pulse oximeter request, but later said it would be better if they could get an organisation to give one for free. Sometimes donations can be of a

[12] In 2013, Kenya's healthcare system underwent 'devolution'; as a result, hospital budgeting and procurement became the responsibility of the local county governments rather than the hospitals themselves.[KPMG,2013]

different form: multiple HCWs described obtaining a pulse oximeter when a foreign doctor on temporary placement brought a personal one; sometimes, not always, this pulse oximeter remained when the doctor left. Sometimes this was the only pulse oximeter in the ward.

Several HCWs considered donors as an embedded, integral part of the health system, as evidenced by, for instance, when several interviewees asked whether pulse oximeters would be donated as part of this study, and other HCWs asked about obtaining drugs or training scholarship funding. However, based on the interviews, relying on donors for equipment procurement may not be sustainable, given issues with repairs of donated pulse oximeters (discussed below), and that relying on donors may provide an excuse for hospitals/Counties to not buy equipment themselves/budget efficiently.

A lack of pulse oximeters is not specific to paediatric wards: one CO explained that there are no pulse oximeters in their hospital's labour or general adult wards. Moreover, there are shortages of other equipment too: HCWs complained about not having enough spirometers, thermometers (particularly infrared ones), glucometers and drugs.

> "*There are some {drugs} which are readily available, but some antibiotics you find they are not so available.(…) Sometimes you find it's there, sometimes it's over, so you find it shifts your treatment for the child. You find you have given for 2 days and you needed to give like 7 days and it's not available for 1 day, so you see, that treatment will be changed.(…) You have to ask in the pharmacy and know if it's not available; if it's not available, the patient has to buy it.*"[14;CO]

Conversely, two interviewees argued that although having a few more pulse oximeters would help, they did not want many more because they worried these would be misplaced, e.g. not taken care of, or taken by nurses to use in private clinics. Furthermore, in contradiction to other HCWs within their ward, a few HCWs thought that enough pulse oximeters were available.

However, almost every HCW described situations when they could not use pulse oximeters even if they wanted to and even if their ward technically owned one or more. Such barriers included pulse oximeters breaking and taking a long time to be repaired, problems with batteries running

out of charge, and missing pulse oximeters, each of which will now be discussed. These issues exacerbate pulse oximeter shortages.

Thus, a common barrier HCWs mentioned was when pulse oximeters **break**. This could refer to pulse oximeters stopping working, but often referred to them malfunctioning and producing strange results. Relatedly, HCWs discussed pulse oximeter reliability and suggested causes for pulse oximeters breaking:

> "*As with any machine, they are man-made, that's one thing. And since humans tend to error once in a while, so you can have machines which are faulty, either due to human error or due to, I don't know,(…) if the device was dropped down maybe it's faulty because of that, so mechanical damage can give you false reading, other times, I don't know, poor quality pulse oximeters, they just give you funny readings*."[3;MO]

> "*Honestly, especially the ones in our hospital, they are not so reliable, I think. (laughs) Especially, we have this new digital one, but they keep oscillating in terms of the results*."[13;MO]

> "*Sometimes the probes get spoilt cuz of how we handle them. So, if people handle them well, there'll be less breaking down.*"[1;MO]

> "*It's troubling, because some of these machines, they stay for long, or they have been here for so long, so now(…) it refuses to take the SpO2*."[14;CO]

One interviewee said pulse oximeters are more likely to break because, as they are too few, too many people use them, particularly those who do not know how to handle them. Interestingly several HCWs noted that sometimes when HCWs think pulse oximeters are broken, they are actually just being used incorrectly:

> "*I wouldn't really point where the problem is; is it about, we operating the machine, or is it that the machine is broken, or spoilt*."[10;N]

Some interviewees reported that pulse oximeters' accuracy can be checked with another pulse oximeter or by applying it to themselves, whereas others presumed the readings were inaccurate whenever they contradicted clinical signs. (Section 6.3.3 elaborates on this.) HCWs spoke of long periods of time, sometimes months, during which one or multiple pulse oximeters were malfunctioning.

When asked how often pulse oximeters break some reported that it happens rarely, while others said it was common. Timeframes ranged from once or twice a year to once in the last 10 weeks, and once every few months. One HCW said it was often enough that although their ward has two pulse oximeters, "*Rarely do you ever have 2, once in a while you can have 2, but they can break down, one can break down, the other one is working*"[2;P]. Some specified that particular types break more often than others. When HCWs mentioned which pulse oximeter part(s) break, they specified the probe (e.g. the spring between the two pieces) or the cable between the probe and monitor.

HCWs said the hospital's maintenance department repairs pulse oximeters. Many explained that this can take a long time. Arguably the **inefficient repair process** is a more significant barrier than pulse oximeters breaking.

> "*That one can take, it can take some time. It really takes time. Because sometimes it can even take a month, or 2 weeks, 3 weeks – you rarely get it done in 1 day or 2.*"[2;P]
>
> "*It's a bit difficult; actually repairing at the County level, they've never been repaired.(…) Once they are faulty, the process of repairing, it's quite a long process, cuz you have to talk to the finance department, the County have to actually assess or to give approval of funds to be available for them to be repaired. It's quite a long process. Yeah. It's not something that it would be spoilt this week and next week it's done; it can even take months before you get another one.*"[9;MO]
>
> "*Ah, it takes a while. Because it depends on how quick the nurses will call, or whoever has been informed, how quick they inform the maintenance people that they have to come. So can find that sometimes you want to use it now, {}, then you're told, oh the probe is spoilt, wait, you have to, you can actually wait until the following day, or the day after.*"[1;MO]

One HCW explained that 80% of children were obtaining pulse oximeter readings until their one pulse oximeter broke; when we spoke it was eight months after the pulse oximeter broke, and it still had not been repaired or replaced, so no children had obtained readings during those eight months. One interviewee discussed how HCWs tried to fix a pulse oximeter themselves instead of sending it for repair, but they were unsure how successful this was:

> "*There's one also that has, I think one, I think it fell. We tried to strap it with, I don't know the reliability on that.(…) It fell and then people try to put it together. So you have to use your hand to try and put it in place*."[8;CO]

When pulse oximeter spare parts or replacements are needed, delays are probably related to the aforementioned procurement process issues. But there can be other reasons for repair delays. A paediatrician gave this explanation:

> "*For one reason or another it takes time. According to me, the reason is because, I don't know, maybe the spare parts, they will say some spare parts are not available. But I can say it's a problem with the Biomedical department maybe, because if you have an audit of the equipment you have, and you should be doing maintenance, you should have an idea what the spare parts that are needed, and maybe procure them in time, or have a way of repairing them as soon as they break down. So it's either the, they're not up to date, or competent enough, or their training also has some issue maybe, because sometimes they will not be able to do anything, or they can't tell you what has happened, so you don't know who is going to help you*."[2;P]

A few HCWs did however say that repairs are efficient. One said the time repairs take depends on how technical the fix is but that it normally takes less than a day.

Some HCWs reported that this issue is even more pronounced for donated pulse oximeters, which often cannot be repaired because the maintenance department is often less familiar with the model and so might not have the appropriate skills to repair them. Sometimes however, the donation is conditional on the hospital agreeing that if the pulse oximeter breaks, it will be sent to the donor for repair. One HCW said it can take 3-6 months for donors to repair and return pulse oximeters, while another said the arrangement is beneficial:

> "*They give me their phone number so I just phone, and they come; in fact, if I can phone like today, you can see them coming {in the evening}. Yeah, they are committed, very committed.(…) In fact, for another ward, NBU, nursery, it was faulty, they even gave them another one, so that they can go with this other, the faulty one, and, put it in order. They are as effective as that.*"[15;N]

Some HCWs recognised that regular pulse oximeter maintenance is crucial (by ward HCWs and/or the maintenance department), to check they are functioning ("*As much as you check your car or your health, you have to check on the machines.*"[14;CO]), but that this generally does not occur.

Another potential barrier concerns pulse oximeter **batteries running out of charge**, which interviewees claimed occurs anywhere from not often to frequently or bi-weekly. HCWs using pulse oximeters running on electricity did not have this problem; at these hospitals, electricity supply is consistent as generators take over during power cuts. However, many HCWs using battery-operated pulse oximeters found these are often unavailable for periods of time when the batteries run out and need to be charged or replaced. Some pointed out that it is not surprising that the batteries run out often because there are so few pulse oximeters so each is being used a lot.

An MO said they try to "*counter that by ensuring we charge them often; after you use a couple of times, charge, because you know definitely that {the {}} are going to run out {}. So just {exchange then charge, charge, afterwards}, most of the time they charge at night"*[1;MO]. But when asked whether, despite this system, they still sometimes cannot use a pulse oximeter because the batteries are not charged, they laughed and said this has happened more than once or twice.

And just as HCWs commonly have problems procuring new pulse oximeters, HCWs often find difficulties getting new batteries, whether because of procurement process issues, or because no-one takes the initiative to sort it out:

> "*The whole of last week, they didn't have battery, we couldn't use it, so it took a week for them, the battery to be replaced.(…) It's not a big process, it's just that (laughs) no one takes the initiative. It's just removing and putting. But, now that one you'll tell the nurses cuz the {they're the ones who arrange} the batteries {probably}. But I don't know, {I can't say why}.*"[12;MO]

While some HCWs said replacing batteries does not take long, others said getting new batteries can take a week or a month; another said it takes so long (because the hospital does not want to pay for them) that HCWs have to buy them themselves. Yet another said "*They say it takes too long to get new batteries. So what we did was removed one from a thermometer we had been using*." [8;CO] The problem begins before the batteries fully run out: multiple HCWs said "*if the batteries are running low, it will give you a false reading*"[3;MO].

Another barrier, frequently mentioned but infrequently occurring, is when HCWs from other wards **borrow** the paediatric ward's pulse oximeter(s), which occurs most commonly when other pulse oximeters are broken, and which is more problematic when paediatric ward HCWs do not know it has been borrowed/who has borrowed it. Small pulse oximeters can also go **missing** when someone walks away with them in their pocket without them/others realising.

> "*You have sometimes to share, yours is broken down, before it comes to be checked and be maintained, you have to share. So if they are using it in the other ward, now you have to wait. It's hard*."[14;CO]

Some reported that pulse oximeters are shared between the paediatric and adult wards whereas others said sharing was limited to between paediatric wards and the newborn unit, as "*No, it's a rule, you can't {share with adult wards}, because we prevent infection. Children are delicate*"[14;CO]. One interviewee acknowledged that, to prevent infection, they should not be exchanging with the newborn unit either, but they do anyway.

Accordingly, several HCWs said the ward could have an adequate supply of pulse oximeters if they were all maintained and easy to access, but that this rarely occurs.

A further environmental constraint is when **the size of the pulse oximeter probe is not appropriate for the age of the child** (Appendix 1.1 shows different probe designs and sizes):

> "*Most of them don't come with probes for a neonate, for a bigger child, so(…) sometimes we really struggle to try and get an SpO2, because the machine we have only has a probe that is big, for a big finger*."[2;P]

When a probe is too big, a HCW who wants to use a pulse oximeter might not be able to attach it to the child. Sometimes HCWs might not realize or might overlook the probe's inappropriate size and use it anyway; any reading produced is likely to be inaccurate. This is of particular concern if the HCW does not realize a reading is incorrect. HCWs reported similar problems with other equipment, e.g. blood pressure cuffs.

There are additional reasons why sometimes, although pulse oximeters are technically available, a HCW may feel it is **impractical** to use one. Thus, a heavy workload can prevent HCWs from

having the time to use pulse oximeters; this can be particularly problematic at nights and weekends as there are fewer HCWs on these shifts (Box 6.6 contains descriptions of the reduced care at nights/weekends.) However, some interviewees think the healthcare delivery standard is consistent at all times.

> "*Every admission should, we should use a pulse oximeter, on every admission. That's the ideal. But, it's not practical, it's not practical.(…) In the afternoon, we come and find we are just two, so it's not very practical that we use a pulse oximeter on everyone, but at least we try*."[10;N]

> "*Casualty is busy. But you have to take for every child. Or maybe they forget. You know, we are human beings, we forget at times, yeah. So maybe they forget, or they are too busy*."[14;CO]

Furthermore, the pulse oximeter's location can discourage use. In one of the paediatric wards, all pulse oximeters are stored in the 'acute room' (the room for children with the most serious conditions). This could be a barrier as some pulse oximeters are bulky and not easy to move, and it is not always practical to take children to the acute room, or the extra effort of doing so may discourage use. One interviewee explained that sometimes children do not cooperate: they cry, move or get scared and throw off the pulse oximeter, so it is hard to attach the probe and get a reading. Moreover, when urgent care is needed, HCWs may also be less likely to use pulse oximeters:

> "*The child may need a lot of resuscitation, so they didn't think of taking it first, when they needed to do something else which was more urgent.*"[14;CO]

Box 6.6: Some descriptions of how care is different at night and on weekends compared with at other times:

"*So whoever comes to change on the weekend as well, for those who are there, might just feel, let's wait for more, for Monday, everyone will be there, I make a decision. So some, they can be a bit different. Although, we try not to make it different. Yes. We try to treat them equally and say if you see something wrong during the weekend, just act on it.*"[1;MO]

"*During the night, the staff, the number of people working at night, is almost half the number of people working during the day. And then during the night, the people working during the night, have been working during the day. For some reason they have not been, so even they have, maybe they are sleepy, maybe they're, but that's what happens. During the night the care has gone down. We have more mortality during the night, we have more resuscitations during the night, and I've always thought it's about, because maybe the staff, I don't know. I've always thought, at night we are a bit, we are very few*."[8;CO]

"*At night, it's only 1 Officer on call, and when you're on call, that's when now it's only 1 person, so you find that, yes, in certain ward is needed, is needed at Newborn Unit, still the same person is needed at Casualty; so you'll find that maybe the [use] of making the diagnosis and management might be a bit low, low.[…] So on weekends and at night you find that there might be under-diagnosis or over-diagnosis of some conditions, and mis-management of even some babies. Yeah. Cuz the person might be overwhelmed with everything*."[9;MO]

The final environmental constraint to HCWs appropriately using pulse oximeters, is when **oxygen is not readily available**, and so HCWs cannot provide oxygen to children in response to pulse oximeter readings. The formal interview participants all said they rarely, if ever, have difficulty obtaining oxygen. One interviewees even said their paediatric department gets more oxygen than other departments in their hospital. However, many of the semi-structured conversation participants (who work in a wider range of facilities than the formal interview participants) described barriers to oxygen provision. Several explained that their ward does not have enough oxygen, e.g. only one or two concentrators/cylinders; and one reported that if more than one child needs oxygen, they need to refer them to another facility.

However, the more common concern was around flow meters (which measure the amount of oxygen given) and splicers/splitters (which divide oxygen supplies so one concentrator/cylinder

can be used with multiple children). Several HCWs said they do not have any flow meters or splicers/splitters, while others said their wards have one or more but some/all are broken. One HCW stated that their flow meters no longer show the correct oxygen measurement so they do not know how much oxygen they are giving, and so have to keep checking the pulse oximeter and the child's condition to determine if they are giving the right amount. Another said they have one flow meter and that if they need to give oxygen to more than one child they might borrow another from the theatre, but that they try not to because, in their experience, when departments borrow flow meters from others, and so they are used by many, they soon break. Multiple HCWs said that when splicers break, HCWs sometimes improvise by e.g. attaching multiple children to one cylinder by sticking needles into it (which they called 'the octopus method'), but then they do not know how much oxygen each child is getting. As one HCW said, this makes nurses feel better, but it does not treat the child properly. Some HCWs mentioned that their splicers are leaking, which wastes oxygen.

The most obvious consequence of not being able to use pulse oximeters is that a pulse oximeter reading will not be available to guide decision-making. When asked what they do when they cannot use pulse oximeters, HCWs overwhelmingly said they rely on clinical signs. Some said if pulse oximeters are borrowed or are charging "*you have to wait. There is no option. Yeah, we don't have other options*"[14;CO], and meantime they monitor the child. However, the interviews revealed some more nuanced consequences, where HCWs' current and future perceptions, intentions and behaviour may be affected, even after pulse oximeter supply is no longer limited. Box 6.7 describes examples.

Box 6.7: Further consequences of inadequate pulse oximeter availability

- Sometimes inadequate pulse oximeter supplies lead to HCWs improvising in order to use a pulse oximeter with as many children who need it as possible, or at least with those who they think need it the most, which can compromise care:

  "*You will find there are more than 2 sick children who need continuous monitoring, and then you're thinking, ok let me remove [] from this one, and then put it on another one, so if you had said let's monitor the oxygen, let's get the pulse oximetry in like 2 hours, in 2 hours, but you have to keep removing, interrupting and going to other patients, then you won't have your monitoring correctly*."[1;MO]

  "*So unless you decide, let me remove for this baby and check for this other baby, but you cannot maintain cuz it's only one. So you'll actually check, you weigh, which baby needs it more, then you'll put on that baby. The other one you'll just use clinical findings and you're like, this one let's put on oxygen, we'll observe. Yeah. Or we'll shift from one baby to the next, cuz we only have at most 2.[…] When, now you would, the children, the other one, is also has severe respiratory distress and is using it. So, that time you feel like you cannot disconnect from this child and reconnect to the other child." And "it doesn't help because at times you need to monitor.[…] So you are in a dilemma in such a case*."[9;MO]

- This pressure to prioritize certain children over others to obtain a pulse oximeter reading can lead to a change in mentality that affects future care, even when pulse oximeter supply is no longer limited. HCWs might continue to use pulse oximeters only with those with whom they had to previously prioritize.
- When pulse oximeters are regularly not available, it can also lead to HCWs simply choosing not to use a pulse oximeter rather than going through the hassle of finding a rare commodity:

  "*If you ask for one and it's not there, let go, let's just continue with our clinical assessment. If it's broken down, let go. And if it's lost, let go. Like sometimes someone has it in another room and they have it in their pocket cuz you know it's a rare commodity so you want to work with it, and you go away, fine, we won't use it. I think that contributes a lot to this variation.*"[1;MO]

  "*If you want a pulse oximeter, you will find it. But if you don't want to go through the hassle of looking for it, then you won't, you won't look for it, you won't use it. So I will just tell you, this is basically based on user. If I'm, if I continue to look for one, someone will say that won't bother.*"[8;CO]

- If in doubt, HCWs just give oxygen:

  "*Then you know this baby is respiratory distress, we start on oxygen, without the pulse oximeter, cuz at times, they are not working, at times they are not there*."[9;MO]

When considering whether pulse oximeter results were interpreted and used appropriately, I wanted to understand how often HCWs give oxygen and specifically how often they do so when pulse oximeter results suggest oxygen was needed (and the converse). While I cannot determine from the interview data the proportion of children who required oxygen, interestingly HCWs' estimates of the proportion of children in their ward who are given oxygen varied dramatically, even across HCWs within the same ward. Answers ranged from "*not many, there are really few*"[12;MO] and "*not that often*"[4;CO] to 3-5%, 20-30%, and 60%, while one HCW said that sometimes it is 50% but sometimes only one child; another HCW specified that 80% in the acute room are given oxygen. The range HCWs stated for children with pneumonia was 30-60%, with most specifying between 50-60%; many said rates vary by season. (Section 5.2 provides evidence from the CIN dataset on oxygen provision frequency). These large ranges, particularly for children overall rather than those with pneumonia, are more likely due to differences in effectiveness of pulse oximeter result interpretation and follow-up, rather than differences in children's conditions across hospitals, as HCWs within the same ward sometimes gave very different values from each other. Box 6.8 shows the symptoms HCWs thought indicate a child needs oxygen.

Box 6.8: Symptoms that HCWs say indicate that a child needs oxygen

The most commonly mentioned symptoms:

- High respiratory rate or tachypnoeia
- Cyanosis
- Indrawing
- Difficulty breathing
- Respiratory distress
- Nasal flaring
- Grunting
- Head nodding

Also mentioned:

- Capillary refill
- Cold/abnormal extremities
- Cardiac disease
- Convulsions
- Cough
- Noisy/abnormal breathing
- Use of auxiliary muscles
- Restlessness

6.3.5 Summary of research findings, as framed within the Integrative Model of Behavioural Prediction

Thus, there essentially was consensus amongst HCWs that pulse oximeters are an important technology that can be useful for helping with clinical decision-making. National and international guidelines that are widely used in this setting help promote pulse oximeter use, as does colleague encouragement, and generally HCWs feel they have the self-confidence to use pulse oximeters. Consequently, all of the HCWs involved in this research intend to use pulse oximeters (i.e. they would choose to use them), at least with certain groups of children (particularly those with respiratory symptoms or who are not alert) if not with all. However, there are barriers preventing pulse oximeter use, most notably inadequate pulse oximeter

supply (because of procurement problems), and insufficient access to the ward's pulse oximeters (most commonly because of delays in repairs and battery charging/replacement). Furthermore, even when pulse oximeters are used, they are sometimes used incorrectly, either due to insufficient skills in pulse oximetry, or because probes are inappropriately sized; this can lead to inaccurate results. Finally, even when pulse oximeters are used correctly, the appropriate follow-up of oxygen provision is sometimes not carried out, either due to insufficient oxygen supply, or because pulse oximeter results are doubted, due to HCW perceptions of pulse oximeter unreliability, and insufficient training on how to interpret pulse oximeter results. Hence, we can conclude that even though pulse oximeters were technically available in all but one of these 14 CIN hospitals over the study time period, and even though there is widespread agreement that pulse oximeter use is important, the number of children benefiting from appropriate pulse oximetry at their admission is a subset of those admitted (as shown by the quantitative findings).

Table 6.3 shows each of the factors and sub-factors within each component of the model in this context; see Figure 6.1 for a diagram of this.

Table 6.3: Factors and sub-factors within each component of the Integrative Model of Behavioural Research within the context of pulse oximeter use in Kenyan hospitals

Component of the Integrative Model of Behavioural Research model	**Factors**
Predisposing factors	Perception of oxygen as an invaluable treatment
Factors influencing HCWs' intention to use a pulse oximeter	Beliefs about pulse oximeters • Why use pulse oximeters? Perceptions of the importance and usefulness of pulse oximeters • For what should pulse oximeters be used? Perceptions of the roles of pulse oximeters

	• With whom should pulse oximeters be used? Perceptions of which children need pulse oximeter readings at admissions and when using a pulse oximeter at admission is not necessary
	Influence of guidance and clinical colleagues • National care delivery recommendations • Hospital policies • Consultants / Heads of Paediatrics • Other HCWs in the ward
	Self-confidence in ability to use a pulse oximeter • How difficult they think it is to use pulse oximeters • Whether they perceive that they have the skills to use pulse oximeters
Skill constraints limiting HCWs' ability to use a pulse oximeter appropriately when they intend to use one	Knowledge of how to use a pulse oximeter / place a probe correctly
	Uncertainty about pulse oximeter results that contradict clinical findings
Environmental constraints limiting HCWs' ability to use a pulse oximeter appropriately when they intend to use one	Pulse oximeter procurement • There are not enough pulse oximeters in the ward • The Procurement process may take a long time and is not always clear
	Access to ward pulse oximeters • Pulse oximeters break • It can take a long time for broken pulse oximeters to be repaired • Batteries run out (and take a long time to be charged / replaced) • Pulse oximeters are borrowed by other wards • Pulse oximeters go missing
	Inappropriately sized pulse oximeter probes
	Impracticality of using a pulse oximeter • Heavy workload • Some large pulse oximeters are not easy to move around • Children do not cooperate • Urgent care is needed
	Insufficient oxygen availability

6.4 Recommendations from HCWs to encourage pulse oximeter use

Interviewees were asked what they thought could be done to encourage HCWs in their ward to use pulse oximeters more often. Most suggestions related to things they are familiar with as HCWs, rather than systematic changes to the health system itself. HCWs commonly stated that obtaining more pulse oximeters would encourage pulse oximetry in the ward. A few said this is all that is needed to increase pulse oximeter use to its full potential. Some suggested it would help to have a meeting with the County officers to convince them of pulse oximeters' importance. Moreover, having more training on how to use pulse oximeters was sometimes suggested, and seen as key to increasing pulse oximetry:

> "*If you empower someone with the knowledge of how to use it, I'm sure they won't forget*."[13;MO]

But the more widespread suggestion was for training on *why* to use pulse oximeters/on their importance:

> "*They just need to know the importance. Educate them on the importance of using the pulse oximetry; that will be enough.*"[11;CO]
>
> *"Why should we take SpO2: if you don't know, are you going to put a lot? You're not going to put a lot of effort. But if you know the reason as to why you are doing this, you'll go ahead and wish to know."*[15;N]

This was sometimes described as "*sensitisation*"[2;P, 8;CO, 5;N], i.e. that "*they just need to be sensitized, that you have not completed admitting a patient, a child, until you have done a pulse oximetry reading*"[2;P], and that "*a mindset change*"[8;CO] is necessary. In other words, these HCWs do not just think others in their ward need to learn more information about pulse oximeters, they think it is also necessary for HCWs to undergo a fundamental change in how they think about pulse oximeters and the admissions process.

The way training is conducted can be as important as its content. Table 6.4 shows what HCWs suggested when asked how best to carry out this training, and by whom. Some stated that trainings should be regular, not one-offs. Furthermore, one HCW argued that the focus should

be on improving medical school training. Most HCWs who suggested training said it was needed for all HCW cadres, or did not specify.

> "*Actually everybody should know about the pulse oximetry, from the nursing team, and the Clinical Officers, and the Medical Officers, everybody should know, about the pulse oximetry. So, there's no {cutoff} for this have, this have, and this no. Because all of us we work for the benefit of our patient. So I think everybody should be a participant in that*."[4;CO]

But occasionally HCWs suggested training is more important for certain HCWs over others:

> "*The most important people to train are normally the interns, and the nursing department. Regardless, even if you tell one intern, and then the other intern trains, or if you train one nurse, and the other nurse comes and trains; so long as you've trained those two, then you should, ideally, have trained the majority of the people who should be using this*."[8;CO]

However, one HCW warned that attendance may be low at formal training:

> "*For the trainings, they could also be a good forum. But I don't know how attendance would be. With how busy people are, they might be like, ah, who is going to learn how to use a pulse oximeter, no I'll ask, I'll find out. The attendance would be a bit low*."[1;MO]

Several HCWs discussed ways to turn pulse oximeter use into a routine. They suggested including pulse oximetry in the daily routine medical charts; and encouraging HCWs to check at shift handovers whether the previous shift's HCW took a pulse oximeter reading, and if not, asking them to do so. Finally, one HCW argued that staffing numbers need to be increased for pulse oximeters to be used more often.

Table 6.4: HCWs' suggestions for how best to carry out training on pulse oximeters, and by whom this should be run

	Suggestion	**Example quote**
Most commonly suggested	Train a few people in the ward and then they can train the others	"*Probably if you will show one or two people, then they can tell one to tell another, tell another, and the word spreads*."[1;MO]
	Each HCW who understands how to use pulse oximeters should train others in their ward	"*We should do them ourselves. Cuz, if as a clinician I understand the need of a pulse oximeter, and I know how to use one, it's very easy for me to just call, maybe 5 guys at a time, on every single day, just show them, one, {I would show} how to use them, and then observe them as they use them and practice to use them. So it is the responsibility of every clinician to ensure that they understand how to use these things and they impart that knowledge on their fellow clinicians*."[3;MO] "*It should be everyone's business. (laughs) It should be everyone's business. As a Medical Officer I would tell my interns, the importance of {the oximeter}, everyone else who's handling the child, the importance of oximetry.*"[1;MO]
	As part of the Continuing Medical Education Sessions (CMEs: regular, e.g. weekly, meetings of all the HCWs in the ward where focus on a particular condition e.g. pneumonia or malnutrition, and discuss best care practices)	"*The trainings should be done in conjunction with the CMEs, especially where, for example, you're, you have a CME on pneumonia, maybe there should be a slide or some 2 or 3 slides on pulse oximeter use. And how to use it and how to interpret it. But I would suggest that it be, it can be done in a hospital CME so that it captures everyone, who is involved in giving oxygen to children.*"[2;P]
	Encourage HCWs to ask for help if needed	
	Should be done specifically in the hospital	"*It will be of more use if it will be done within the hospital. Because we know what challenge they have*."[5;N]
	By/with the maintenance department or engineers from the manufacturer	"*I think it should be something in collaboration with the maintenance people, the medical engineers. Cuz I think they are the people who are able to interpret the manufacturer's pamphlets. So could be the engineers, medical engineers, in conjunction with someone from the same company,*

		that company that has donated, you know, where the model was made, or something like that."[10;N] "*I think it's better when you are taught by the people who know how to really use it, not the nursing station, but, because different people will teach you different {they want to do}, yeah. So if it's made by these people and they know how to use it, {they're} people who really know the machines, engineering, medical engineering, they tell you how to use it, and how to maintain it. That will be easier for us to know, so that when he tells a problem, we will know this is a problem*."[14;CO]
	During ward rounds	"*During ward rounds, I think someone can emphasize the importance of pulse oximetry; if you find a patient who doesn't have a reading, you can talk to people about it*."[12;MO] "*Showing them the importance in the ward round. Because you will make it, you have to show them why it is important, most of them know why it is important, but there are maybe one or two who, their knowledge, maybe they have a gap, they don't understand, but once you tell them you admitted this patient, this patient had, was grunting, had lower chest wall indrawing, you didn't check the oxygen? SpO2? Did the patient need oxygen or not? And if they needed oxygen, how much did you need*?(…) *So, check the SpO2 and you check with them, and by the time you've finished a ward round, usually our patients are very many; if you teach them on the patients, and show them the importance of the SpO2, they're usually willing, and ready to continue*."[2;P]
Also suggested	By consultants / the Head of the Department	
	Pin the manual up on the wall	"*If they come with the guides, whoever opens can actually give the guide, or pin it somewhere, for people to see; we have all this other protocols, management of something, so you can have one that says use of the pulse oximetry*."[1;MO]
	Exchange programmes to see how pulse oximeters are used elsewhere	
	By someone external to the hospital	"*I've found people, people like training when the person who is telling them, they have never seen the person (laughs). Like they see someone foreign coming in and telling them about this, they are more receptive*."[8;CO]

	A poster on the wall	"*It does not mean that training has to be all day sitting in class. Even a simple chart, a simple chart, and pin it, in the newborn unit, pin it in the ward, SpO2, Have you taken the SpO2?, or Remember to take the SpO2. This is something, doesn't need to be too expensive. We just give, make it, make it, if you just make it that, there's something to remind me*."[8;CO]
	By other companies that already come to teach e.g. basic life support	
	Done outside of the hospital (but if so should not just have sessions in Nairobi because can be expensive to get there and get accommodation for HCWs based in other parts of the country)	"*Anything done externally must be done {rightfully} and minimal time and resources here, but, if you use the hospital, then it will take a long time. First of all because the hospital in itself is being run by the, another organisation, maybe the County and the government. So before, something happens, a bit time consuming. So from the external, that will be better*."[4;CO]
	Being available for other HCWs: giving them positive feedback, giving them responsibility, and showing them passion	

6.5 Feedback from the participants on the findings from their interviews

As part of triangulation, I emailed each semi-structured interview participant with the 10-20 main points from their interview, asking if I had misunderstood anything, and if they wanted to add anything. Six (out of 16) interview participants responded; this corresponded to one of the three Hospital A interviewees, one of three from Hospital B, four of five from Hospital C, and none of five from Hospital D, and included one paediatrician, three MOs, one CO, and one nurse. One of these HCWs made two minor corrections to my summary of their points, while the others did not have any changes.

Chapter 7: Discussion

7.1 Introduction

I will begin by summarising some of the key national and international concerns that highlight the importance of generating evidence on the use of pulse oximetry, and will comment on the potential role of relatively widely disseminated national guidelines. I will then present and discuss integration of the quantitative and qualitative research findings (Section 7.2). Following this, I will describe the methodological strengths, challenges and limitations of this mixed-methods research (Section 7.3). Then, I will discuss the implications of the findings for practice (Section 7.4), further research, and the broader diffusion of health technologies literature (Section 7.5).

In 2015, pneumonia was the leading infectious cause of death in children worldwide, causing 16% of under-five deaths, and was the leading cause of death of any kind (infectious or otherwise) in children aged one month to five years (a relevant age group as children under one month were excluded from my quantitative analyses). 0.8 million children one month to five years died in 2015 from pneumonia, almost half a million of whom were in Sub-Saharan Africa.[Liu et.al.2016] Pulse oximeters are a low-cost, easy-to-use technology effective at detecting hypoxemia in children, which is a common complication of various conditions, including pneumonia.[WHO,2014b] It has been estimated that introducing pulse oximeters into 15 low-income countries with the highest burden of severe pneumonia, could prevent 148,000 annual deaths from pneumonia.[13] This study also estimated that pulse oximeter implementation

[13] The researchers assumed that: there would be good availability of pulse oximeters and oxygen, and widespread use of pulse oximeters; two models were produced, one in which introducing pulse oximeters increased the sensitivity of integrated management of childhood illness to 70%, and another where sensitivity increases to 85% (the second model is the one that produces the estimate of 148,000 deaths averted); specificity was assumed to be around 85% for pulse oximeters in combination with integrated

in these countries, in combination with integrated management of childhood illness, could be very cost-effective, at US$3-53 per disability adjusted life year ($15.67 for Kenya).[Floyd et.al.2015]

Efforts to implement effective low-cost interventions support the implementation of the United Nations' Sustainable Development Goal 3, which is to "*by 2030 end preventable deaths of newborns and children under 5 years of age*"[United Nations,2017]. These include national and international efforts advocating for increased pulse oximeter availability in low-income settings, for example, the World Health Organization's (WHO's) Global Pulse Oximetry Project, the BMJ Christmas Appeal, the Lifebox project, the Ethiopian Ministry of Health's National Medical Oxygen and Pulse Oximetry Scale Up programme, and Save the Children's Fighting for Breath campaign.[WHO,2008; Feinmann,2011; Lifebox,2015; Ethiopian Ministry of Health,2016; Save the Children,2017] The use of pulse oximeters is a focus of national and international guidelines on the management of conditions in children such as pneumonia, bronchiolitis and asthma, to help with diagnosing and/or decision-making concerning oxygen provision.[WHO,2012; Clark et.al.2011; Bradley et.al.2011; Healthcare Improvement Scotland,2014]

However, these efforts have not necessarily led to widespread increase in appropriate use of pulse oximeters in low-income settings. Several studies indicate that pulse oximeters are often not used in these settings even when available.[McCollum et.al.2013; Ginsburg et.al.2014; Ginsburg et.al.2012] In my analysis of the 14 hospitals included in the Kenyan Clinical Information Network (CIN), from September 2013-February 2016, 13 had at least one pulse oximeter, healthcare workers (HCWs) did not use pulse oximeters at two hospitals where they

management of childhood illness; adherence to recommended treatment for children with severe illness was assumed to be around 85% with pulse oximetry. Thus, the predicted reduction in deaths through such an intervention will not be achieved without better adoption of pulse oximeters than is currently seen in many low-income settings. This highlights that models need to be more realistic and consider potential implications if adoption is below universal [see Section 7.5.1]

were available, and pulse oximeters were used with 7 to 75% of children at the remaining hospitals, varying greatly over time at each hospital (See Section 3.2.3).

Moreover, having guidelines that recommend pulse oximeter use is not necessarily sufficient for increasing pulse oximetry, as these are often not followed, even if HCWs are aware of them. This is not uncommon. Evidence shows that HCWs in many settings often do not adhere to care guidelines [Flodgren et.al.2016; Grimshaw et.al.2004a], and that guideline adherence following an intervention's implementation often lapses within a year [Ament et.al.2015]. A study conducted in Kenya before the CIN's implementation found that barriers to guideline uptake included beliefs and attitudes that conflicted with the guidelines; and insufficiencies in training, local leadership, effective communication, resources, motivation and perceived benefits of the guidelines.[Nzinga et.al.2009] This is also demonstrated in this thesis where, while knowledge of the WHO and Kenyan Basic Paediatric Protocols guidelines is generally good, implementation often does not occur, due to insufficient training or barriers preventing the recommended behaviour. (See Table 7.1)

Table 7.1: HCWs' knowledge of the WHO and Kenyan Basic Paediatric Protocols guidelines, and whether these guidelines are implemented, according to the integrated findings of the quantitative dataset analyses and qualitative interviews of this thesis

Guideline	Knowledge of the guidelines	Implementation of the guideline
Pulse oximeters should be used to help to decide whether to give oxygen	Yes	Yes
Pulse oximeters should be used to help to diagnose children	Rarely	Rarely
Pulse oximeters should be used with all children at admission	Sometimes	Rarely
If a child has a pulse oximeter reading below 90%, they should be given oxygen	Yes	Sometimes

The clinical signs that indicate oxygen is needed are: cyanosis, nasal flaring, difficulty drinking, difficulty feeding, grunting, depressed mental state, indrawing, high respiratory rate	Yes	Yes

Note: 'Rarely' and 'Sometimes' are used here as relative and subjective terms: 'Rarely' refers to the fact that knowledge or use of the guideline was only demonstrated in a small number of the dataset admissions and/or interviews of this thesis; 'Sometimes' refers to the fact that knowledge or use was only demonstrated occasionally but not commonly in the dataset admissions and/or interviews of this thesis.

This thesis examines pulse oximeter use with children at admission to hospitals in low-income settings, focusing on Kenya, utilising three research components: a systematic literature review, quantitative dataset analyses of 28,000 child admissions to seven Kenyan hospitals, and 30 qualitative interviews with HCWs and other staff from 14 Kenyan hospitals.

The systematic literature review formed the background to this research; it helped identify the literature's gaps on pulse oximetry in low-income settings, and develop the Research Questions for the CIN dataset quantitative analyses, and the subsequent qualitative interviews. After overcoming the missing data problems inevitable in large observational datasets from routine settings, the quantitative analyses of a large clinical dataset, guided (unlike other studies) by a conceptual framework (see Section 3.4), allowed for examination of patterns of many factors with a large population over time. I developed an interview approach informed by the quantitative analyses findings, and conducted interviews with HCWs to explain and validate these findings, and to further explore HCWs' experiences and opinions. It was anticipated that HCWs' explanations of why, when and how pulse oximeters are/are not used in this setting, would help formulate effective recommendations targeting the circumstances of HCWs in this context; and the dataset analyses would provide the estimates of the problem's magnitude and the variation that would guide these recommendations' development.

7.2 Consolidation of quantitative dataset analyses and qualitative interview results

I used a sequential 'mixed-methods' approach in this study: qualitative interviews were informed by the quantitative dataset analyses (see Sections 1.3.5 and 3.3.1). In this chapter, I report the integration of the findings from each research component. I have used a triangulation protocol [Farmer et.al.2006; O'Cathain et.al.2010] to begin the reporting of the findings, as this demonstrates how findings from different research approaches support or contradict each other, or explore different areas, thereby providing an overview of the direction and extent of the research findings. Thus, Table 7.2's triangulation protocol demonstrates the agreement, partial agreement, silence (one of the methods does not examine the factor) or dissonance (the dataset analyses findings do not agree with the interview findings) between the CIN dataset analyses and interview findings. Various studies in implementation science and other health research areas have employed triangulation protocols to integrate findings from multiple research methods, e.g. Squires et.al.(2015); Martin et.al.(2014); Pugh et.al.(2014); Briller et.al.(2008); Sui et.al.(2012). The interviews helped validate the dataset analyses findings, and provide information on the additional area of barriers to pulse oximeter use. The themes shown in Table 2 are each discussed in turn below.

Table 7.2: Triangulation protocol displaying agreement, partial agreement, silence (the factor is not examined in one of the methods), or dissonance (the findings from the dataset analyses do not agree with the interview findings) between the findings from the analysis of the CIN dataset and the interviews; the themes are discussed in turn following this Table

Themes	Findings	Agreement	Partial agreement	Silence	Dissonance
Barriers to pulse oximeter use	The main organisational barriers to appropriate pulse oximeter use are procurement and repair issues				
	The main individual level barrier to appropriate pulse oximeter use is a lack of training on why to use pulse				

	oximeters and how to interpret their results				
Variability in pulse oximeter use	There is a large variability in pulse oximeter use within and across hospitals over time				
With which children are pulse oximeters used	Pulse oximeters are more likely to be used with children who were admitted later in the study period, or were admitted to particular hospitals, especially those where the PAR[i] was used				
	Pulse oximeters are more likely to be used with children who have a high respiratory rate, difficulty breathing, indrawing, or are not alert				
Implications of pulse oximeter use	Pulse oximeter use is associated with increased oxygen use				
	Pulse oximeter readings below 90% are associated with increased oxygen provision				

[i] PAR refers to the Paediatric Admissions Record, which is a form for recording admissions data that was implemented to improve quality of data recording and prompt recommended behaviour

Barriers to pulse oximeter use

It was not possible to explore pulse oximetry barriers using the CIN dataset, so insights discussed here draw only on the qualitative research (see Table 7.2). A range of barriers prevent HCWs from using pulse oximeters, mitigating any potential benefits of pulse oximeter use on child health outcomes or hospital resources. Almost all interviewees told of situations in which they cannot use pulse oximeters even if they want to. The greatest barrier to using pulse oximeters was an insufficient number of fully-functioning pulse oximeters in the ward. In addition to directly affecting pulse oximeter availability for use with children, shortages lead to overuse of

available pulse oximeters, which then break more often, contributing to HCWs' perception of pulse oximeters as unreliable. Insufficient availability of fully-functioning pulse oximeters was partly due to procurement systems that are often slow and opaque (an issue also affecting availability of spare parts and batteries); and partly due to inefficient repair processes that lead to broken pulse oximeters remaining unusable for long periods of time, sometimes months. In some hospitals, insufficient access to oxygen was also an important barrier to appropriate pulse oximeter use, as the pulse oximeter results could not necessarily be acted upon.

Similar barriers are discussed in the limited literature on pulse oximeter use in other low-income settings. Thus, even despite efforts by organisations such as the WHO and Lifebox to donate[14] pulse oximeters to low-income countries [Lifebox,2015; WHO,2008], 53% of 97 clinicians surveyed across 19 countries in Ginsburg et.al.(2012)'s study thought inadequate supply is a barrier to pulse oximeter use. Furthermore, 46% said insufficient training is a barrier and 48% said there were broken pulse oximeters at their facility. Sixty-six percent of the 81 clinicians Ginsburg et.al.(2014) surveyed in Cambodia said that pulse oximeters breaking is a barrier to pulse oximetry in their hospitals while 61%, and 49% reported that their unreliability, and insufficient supply, respectively, are barriers. There is also some evidence for HCW behaviour influencing rates of pulse oximeter malfunction; thus, when Gray et.al.(2017) introduced oxygen systems including pulse oximeters into 20 hospitals in Laos, after three years, the proportion of pulse oximeter probes that were still functioning varied from 0-100% across the hospitals; they argued that while environmental factors could have contributed to this variation, it is likely that differences between hospitals concerning consideration of maintenance and loss were influential[15]. It is also worth noting that in Kenya, unlike with drugs, no central process exists for

[14] And as discussed in Section 6.3.4, relying on donations for pulse oximeter procurement is not sustainable and does not build a system of use.

[15] This is also linked to the importance/influence of leadership and championing shown in the findings of this thesis and discussed elsewhere (also in the Kenyan context): McGivern et.al.(2017); Nzinga et.al.(2013)

recommending, providing, or supporting purchase of medical equipment such as pulse oximeters, which could also have assisted with repairs (an example of a factor at the highest outer setting level of the health system hierarchy, see Figure 7.2). Repairs and spare part problems are often mentioned in studies examining dissemination and uptake of pulse oximeters and other oxygen equipment or other similar health technologies [Duke et.al.2008; Weber&Mulholland,1998; Hodges et.al.2007; Thoms et.al.2007; Duke et.al.2009; Malkin&Keane,2010; Bradley et.al.2015; Crede et.al.2014] (see Box 7.1), though specifics on issues occurring in the repair or spare part procurement process, or how much these cost, are often lacking. Ultimately, these issues point to the lack of a wider procurement/maintenance ecosystem in low-income country health systems; building these elements is a neglected area of health systems strengthening.

Box 7.1: Descriptions of pulse oximeter and oxygen system repairs in other low-income settings

- Weber&Mulholland(1998) reported that the five pulse oximeters they used in hospitals in the Gambia each needed repairs once every two-three years and to be repaired, they had to be sent to the Netherlands; this repair cost around $500. Probes broke every six months and repairs cost $250.
- Crede et.al.(2014) examined repairs in South Africa of pulse oximeter probes specifically and found that the problem with most of the almost 2,000 probe repairs they analysed was issues with the probe wiring. Only 2% of the broken probes could not be repaired. Repairs cost $48 per repair, excluding replacement parts and shipping.
- In Malkin&Keane(2010)'s study, 100 engineers, engineering students, and technicians collected data on broken medical equipment, including pulse oximeters, in 60 low-income hospitals in 11 countries, and found that they could repair 72% of the equipment without needing further specialised training or tools, or spare parts imported from abroad. This suggests that repairs of medical equipment like pulse oximeters is generally straightforward and can be conducted by a trained hospital biomedical department, rather than needing input from elsewhere/abroad, as is often suggested.
- Gray et.al.(2017) found that in the first year of their implementation of oxygen systems including pulse oximeters into hospitals in Laos, what limited equipment repairs was insufficient spare parts, rather than inadequate local engineering skills.
- Various studies have also reported issues with inadequate maintenance of other elements of oxygen systems in low-income settings. [Bradley et.al.2015; Graham 2017; La Vincente et.al.2011]

A lack of HCW motivation may sometimes help explain some of these issues, e.g. that it can take a long time for someone to take initiative to get new batteries. Mbindiyo et.al.(2009) examined HCW motivation in Kenyan hospitals; of the reasons they found that HCWs may have lower motivation, some most relevant for this research were insufficient support and collaboration between HCW cadres, a lack of effective communication between hospital managers and HCWs, insufficient commitment of hospital managers to support and improve working conditions, and physical constraints e.g. inadequate supply of staff or equipment. A systematic review examining HCW motivation across 17 low-income countries found similar influences, along with insufficient training.[Willis-Shattuck et.al.2008] Therefore an element of poor practice may be that HCWs are blaming the process, to excuse themselves from engaging with it, as a form of self-protection in a context where they do not have the motivation to tackle the problem.

Clearly a focus on increasing pulse oximeter use is ineffective if oxygen is not available. [Moschovis&Hibberd,2016] There was an insufficient oxygen supply in some of the examined CIN hospitals, a common issue in the literature.[Graham et.al.2017; Bradley et.al.2015; La Vincente et.al.2011] However, in these CIN hospitals, HCWs often felt the more substantial barrier to giving oxygen to all children who need it was an inadequate availability of fully-functioning flow meters and splitters[16] (to measure how much oxygen is given, and so HCWs can attach multiple children to one oxygen cylinder/concentrator, respectively), either due to malfunctioning (also noted elsewhere [Bradley et.al.2015]) and a lack of repairs, or due to inadequate supply. (See Section 6.3.4).

Furthermore, some of these barriers may be perceived or subjective rather than objective barriers. This is suggested by how descriptions of some barriers were not consistent within

[16] These can be hard to find for purchase.

hospitals. For instance, each HCW who stated that their ward had enough pulse oximeters was working in a ward where other HCWs contradicted this.

There are many types of pulse oximeter, of many sizes, power sources, portability, probe type, price, complexity, and reliability. Different pulse oximeter types may be available within the same ward (this points to the absence of any system-wide procurement/contracting mechanism, and renders maintenance more difficult). This variability in available pulse oximeters complicates our discussion of pulse oximeter characteristics and barriers to use, as these would clearly differ by pulse oximeter type. Interviewees sometimes discussed their preferences for certain pulse oximeter types over others (e.g. some preferred smaller ones which are more portable, while others complained that these are more easily lost; one interviewee reported that their complex pulse oximeters produce outputs that are too confusing to easily interpret, while others thought such pulse oximeters are helpful in displaying other measures in addition to pulse oximeter results). Arguably it might be helpful for these wards to obtain pulse oximeter types that sound an alarm when dangerous oxygen saturation levels are reached (these are usually used for monitoring but could potentially be useful for the 'spot use' pulse oximetry discussed in this thesis – the alarm could remind HCWs of the recommended threshold), but there are also descriptions in the literature of disadvantages to these, e.g. 'alarm fatigue' where HCWs get tired of frequent, and sometimes false, alarms and so ignore them, which can worry parents, and sometimes harm the child.[Mitka,2013; Salyer,2003] Recognising the problem of using inappropriately sized probes, Lifebox has recently developed a new probe, for use in low-income settings, that can be used in children of all sizes, from neonates up.[Lifebox,n.d.b]

Accordingly, pulse oximeter promotion programmes need to carefully assess which type of pulse oximeter(s) they want to introduce/promote. Duke et.al.(2009) list factors to consider when deciding between pulse oximeters, including weight, operating temperature and humidity, and whether the pulse oximeter has a hard, robust case to avoid damage. A difficulty in determining

the optimum pulse oximeter for a context is the lack of thorough evaluations in the literature of different pulse oximeter types and characteristics. Some studies assess and/or compare the accuracy of specific pulse oximeters [Gehring et.al.2002; da Costa et.al.2016; Harris et.al.2016], but overarching systematic reviews or guidance are lacking [WHO,2012].

Importantly, HCWs mentioned that other basic diagnostic tools like thermometers, spirometers, glucometers, and blood pressure cuffs have some of the same barriers to use as pulse oximeters e.g. insufficient availability, delays in battery replacement, preferences of certain types, and inappropriate sizes for children. Therefore, as with pulse oximeters, even though these technologies are low-cost, effective and considered easy to use, hospital administrators, programme planners, and researchers should not assume they will be available, and if available, that they will be used. Strategic thinking is particularly needed when introducing essential technologies and maintenance/procurement systems in low-income settings which do not have local biomedical engineering departments (which could otherwise carry out processes in-house or do effective local contracting).

Variability in pulse oximeter use

Discussion of these barriers during the interviews helped explain the CIN dataset analyses findings that, while pulse oximeter use increased over time in the CIN hospitals, this was not a steady increase, as at every hospital where pulse oximeters were used, levels of use varied over the time period, sometimes quite dramatically; and that pulse oximeters were not used in four CIN hospitals over the study period (even though at least one pulse oximeter was technically available in all but one of these hospitals), and only started being used towards the end of the study period at three further CIN hospitals. (See Section 3.2.3)

According to the findings, the main reasons why pulse oximeters are used more often in some hospitals than in others is probably because the consultants in some hospitals advocate for the

importance of pulse oximetry, which speaks to the importance of leadership [McGivern et.al.2017; Nzinga et.al.2013], and some hospitals have more pulse oximeters than others, due to for instance more efficient procurement systems, County officials that understand the importance of pulse oximeters, and relationships with donors who provided one/multiple pulse oximeters. In those hospitals where pulse oximetry was rarely/never used, the main reason according to the interviews was a lack of pulse oximeters. HCWs from these hospitals reported that they understood the importance of pulse oximeters, and wanted to use them, but simply did not have any.

Based on the interviews, the variability within hospitals over time (e.g. the repeated drops in use after increases), is likely most commonly due to delays in pulse oximeter repairs. Some HCWs mentioned that pulse oximeter use may drop when new rounds of intern rotations start, but they said this is unlikely to cause the large reductions found; it may however contribute to the variability. When I checked the events logs produced for each hospital (which show when staff rotations, strikes, new programmes, and other events occurred), events did not line up with the lower rates of pulse oximeter use, lending further support to the role of repair delays.

Pulse oximeter use increased over time; this was most likely due to the feedback provided by the CIN to hospitals. This feedback is on documentation completeness and adherence to care recommendations (including on pulse oximetry). It is communicated through reports sent to hospitals every 2-3 months, yearly face-to-face meetings with HCWs, and regular telephone discussions with paediatricians (see Section 3.3.4).[Gachau et.al.2017; English et.al.2017b]. In the interviews, HCWs reported that CIN reports and meetings educated and motivated them to improve care and compete with other hospitals.[McGivern et.al.2017] Gachau et.al.2017 have also discussed improvements in various indicators following CIN feedback, particularly for simple tasks with low initial performance. The second influential factor is likely to be the dissemination of the Kenyan Basic Paediatric Protocols.[English et.al.2014] HCWs widely discussed these

Protocols, and would often pull a copy out of their pocket to show to me. HCWs spoke of an increased awareness of the guidelines, and appeared to trust the recommendations.

With which children are pulse oximeters used

Many of the interviewed HCWs believe that, when available, pulse oximeters should be used with all children at admission. However, some HCWs described clinical situations when they believe pulse oximetry is not essential, e.g. for children without respiratory symptoms, or more specifically, those with e.g. diarrhoea, vomiting, or physical trauma. Most of these clinical situations were not included in the dataset analyses examining with which children pulse oximeters are used and so validation cannot be sought there; the exception is that the dataset analyses also indicated that HCWs are less likely to use pulse oximeters with children who are vomiting than with those who are not. Both the dataset analyses and the interviews suggest that, when pulse oximeters are only used with a subset of children (out of choice or because barriers restrict their use to those whom HCWs assess as most in need), the children most likely to obtain a pulse oximeter reading are those with a high respiratory rate, difficulty breathing, indrawing, who are not alert, and/or were admitted to particular hospitals. (See Table 7.3).

While the dataset analyses indicated that PAR availability is associated with increased pulse oximeter use, the interview participants explained this association in reporting that the PAR's box for a pulse oximeter result reminds them to use pulse oximeters/emphasizes that they should use one with each child. Incidentally, the PAR was implemented to improve medical information recording and to prompt recommended behaviour [Mwakyusa et.al.2006], so these findings indicate that PAR implementation has been successful. The literature contains evidence for the effectiveness of providing reminders to HCWs in various settings to influence their clinical behaviours (e.g. Cheung et.al.(2012); Flodgren et.al.(2016); Pantoja et.al.(2017); Ivers et.al.(2012)); however, while some studies have found that checklists are effective at encouraging HCWs to use care guidelines (e.g. Haynes et.al.(2009); Spector et.al.(2012);

Treadwell et.al.(2014)), other studies have mixed findings (e.g. Pantoja et.al.(2017); Ko et.al.(2011)). Another insight provided by the interviews was that many mentioned 'respiratory distress' as a characteristic they look for to indicate that pulse oximetry/oxygen provision is necessary, but when asked what symptoms are indicative of respiratory distress, the type and number of symptoms stated varied by HCW, as did the confidence with which they gave their answer. This may suggest that for some, deciding whether to use a pulse oximeter/provide oxygen is not a strict evaluation of the presence/absence of specific symptoms.

Interestingly, parental influence was not mentioned in any of the interviews. This differs from the literature, where evidence suggests parents' perception is important for HCWs' use of pulse oximeters. Accordingly, HCWs in Uganda, Ethiopia, Cambodia and South Sudan who participated in Spence et.al.(2017)'s study thought that, for pulse oximeters to be usable and scalable, parents should be able to see the pulse oximeter's readout and understand its meaning. Enarson et.al.(2008) and Duke et.al.(2009) argue that pulse oximeters crucially demonstrate the benefits of oxygen provision to parents who may otherwise be afraid that oxygen harms children, after seeing severely ill children die after being given oxygen.

Thus, based on these findings, programme planners aiming to increase pulse oximeter use so that they are used with all children at admission, as is recommended, should promote the use of the PAR or similar checklists (although these alone may be insufficient). Training programmes on when to use pulse oximeters should explain why children with symptoms other than those prioritized by HCWs also need pulse oximeter readings. Crucially, HCWs widely perceive that pulse oximeters are important and should be used, so programmes do not need to convince HCWs of this, but rather when and why to use them. The ultimate goal is for there to be reliable availability of pulse oximeters and, in the HCWs' words, 'sensitization' and 'a mindset change', resulting in all HCWs considering it the norm to use pulse oximeters as a routine with all children at admission.

Table 7.3: The variables shown to be influential on pulse oximeter use, according to the dataset analyses vs. the interviews

Variable	**Found to be influential in the dataset analyses**	**Found to be influential in the interviews**
Hospital	√ (strong)	√ (strong)
Admission time period	√ (strong)	√ (strong)
Age in years	√	√
PAR use	√ (strong)	√
Weekend admission	√	√
Fever	√	
Cough	√	
Difficulty breathing	√	√ (strong)
Vomit everything	√	
Convulsions		√
High respiratory rate	√ (strong)	√ (strong)
Chest indrawing	√ (strong)	√
Lack of alertness	√ (strong)	√ (strong)
Difficulty drinking	√	

Note: gaps indicate that the dataset analyses or interviews did not find the variable to be influential on pulse oximeter use; the variables that were found to not be influential in either method were: sex, weight-for-age, length of illness before admission, difficulty feeding, oedema, stridor, grunting, wheeze, crackles, capillary refill, pallor, stiff neck, and bulging fontanelle.

Implications of pulse oximeter use

When HCWs use pulse oximeters at admission they predominantly use them to help decide whether to give children oxygen, or to provide a baseline for monitoring. This is more limited than the roles the literature describes or recommends, which include diagnosing e.g. pneumonia, assessing asthma severity, assisting with general monitoring, etc.[WHO,2013; Jubran,2004; Bradley et.al.2011; Healthcare Improvement Scotland,2014] The lack of emphasis on pulse oximetry's role in diagnosis may be because these children were referred to the ward with a provisional diagnosis, and because a norm exists of using only clinical signs to diagnose.

In deciding when to give oxygen, HCWs are not consistently following the 90% oxygen saturation threshold recommended by the WHO and Kenyan Basic Paediatric Protocols[WHO,2013; Kenyan

MoH,2016]. Instead, clinical signs may be prioritised over pulse oximeter results. This mirrors the debate continuing in the literature on whether the 90% threshold should be used (see Section 2.4): disease management guidelines differ in thresholds they recommended, if any [NICE,2014; Bradley et.al.2011; NHS,2013; SIGN,2006; Subcommittee on Diagnosis and Management of Bronchiolitis, 2006; Healthcare Improvement Scotland, 2014], reflecting the lack of evidence. While a few, generally observational, studies compare outcomes depending on threshold used (e.g. Cunningham et.al.(2015)'s study showing that cough resolution time in children with bronchiolitis was equivalent when a <94% or <90% threshold was used), the debate will not be resolved until more studies, particularly randomized controlled trials, are conducted examining the value and impact of using different thresholds. The COAST randomised-controlled trial is currently recruiting participants to examine this very issue: the researchers will investigate mortality at 48 hours and 28 days in 4,200 children in East Africa when oxygen is given regardless of oxygen saturation value vs. when oxygen is only given when values are <80%.[Maitland et.al.2017]

An issue the interviews highlighted was that a common reason for HCWs not using the 90% threshold is when they are uncertain of low pulse oximeter readings that contradict clinical signs. This is important because sometimes, this lack of confidence could cause misinterpretation of the results, and so the child not benefitting from the pulse oximetry. Researchers and programme planners therefore need to consider and measure *how* pulse oximeters are used, not just *whether* they are, as just because HCWs use a technology does not mean they use it as advised by guidelines. Nonetheless, several studies show that allowing lower oxygen saturation levels (termed 'permissive hypoxemia'), particularly in children with less severe disease, might not be harmful.[Maitland et.al.2017].

The lack of confidence in pulse oximeter results may stem partly from previous experience with malfunctioning pulse oximeters (and malfunctioning is more likely to occur when there are too

few pulse oximeters as these will be over-used) and inappropriately sized probes, and thus a perception of pulse oximeters as unreliable. Another contributing factor is HCWs' insufficient knowledge that children can need oxygen without exhibiting clinical signs, and about situations in which pulse oximeters may be less accurate. Thus, even good quality, fully functioning pulse oximeters may be less accurate when e.g. a child has carbon monoxide poisoning or hypothermia/vasoconstriction, or due to excessive movement (e.g. shivering, convulsions, agitation), nail polish, dirty sensors, and at readings <70%.[Jensen et.al.1998; Blaisdell et.al.2000; Chan et.al.2013; Langley&Cunningham,2016; Olive,2016; WHO,2011b] Furthermore, as interviewees discussed, sometimes pulse oximeters give inaccurate readings, not because they are malfunctioning, but because the HCW is using it incorrectly. HCWs reported that in medical school they were often only taught how to obtain a pulse oximeter reading, but not why, or how to interpret the results. Furthermore, training within the ward generally consists of, at most, colleagues informally showing others how to attach pulse oximeters.

Paediatricians and MOs were more likely than COs to describe situations when they were concerned that low pulse oximeter results contradicted clinical signs, and nurses were least likely. This is consistent with other studies' guideline adherence findings (Choudhry et.al.(2005); McDonald et.al.(2005); King et.al.(2018)), that those with more medical training/seniority have the confidence to question the technology and its guidelines and trust their judgement instead. Thus, all HCWs of all cadres and seniority should obtain training on interpreting pulse oximeter results.

Evidence from other contexts suggests that insufficient understanding of why and how to use pulse oximeters is a problem. Only 11% of Ugandan nurses participating in Nabwire et.al.(2017)'s survey could show they could accurately and appropriately use pulse oximeters. Fouzas et.al.(2010) found that Greek HCWs did not have adequate practical or theoretical knowledge of pulse oximeters, particularly concerning how to use them and their limitations. Seeley

et.al.(2015) found that Australian nurses had poor knowledge of how to apply and interpret pulse oximeters; the researchers argued that, based on their findings, this knowledge needs to be obtained in pre-graduate education rather than through on-the-job experience. Sometimes HCWs are aware that they need more training; thus 95% of the 81 Cambodian clinicians surveyed in Ginsburg et.al.(2014)'s study said they have had insufficient training on pulse oximeter use. Conversely, Popovich et.al.(2004) found that, although 84% of HCWs they surveyed reported that they had obtained sufficient training on pulse oximetry, they made numerous mistakes when asked to interpret pulse oximeter results in hypothetical situations, indicating that, as was common in the interviews of this thesis, HCWs may be unaware of their insufficient knowledge on pulse oximetry.

To foster confidence in pulse oximetry for supporting clinical decision-making, it is therefore important that, going forward, only good quality, accurate pulse oximeters are obtained; pulse oximeters are regularly monitored for malfunctions and repaired promptly (see Section 6.3.4); and theory and practice training is provided on how to use pulse oximeters, their limitations, and how to interpret their results (see Section 6.3.3). HCWs discussed which modes of training they think are most effective: they largely thought training should take place within the hospital, and the most common suggestions were for training to be conducted during Continuing Medical Education Sessions (CMEs: periodic informational meetings held in the ward for all HCWs), by consultants during ward rounds (both of these suggestions link back to the importance and influence of leadership in the ward, as shown by McGivern et.al.(2017) and Nzinga et.al.(2013)), by the maintenance department/manufacturers, or by each HCW sharing their knowledge with others. This training should be integrated within the existing workflow so it is not a burden for HCWs who already have busy workloads.

Despite the lack of confidence in pulse oximetry, the findings from the CIN dataset analyses indicate pulse oximeter use is associated with increased oxygen use, in children with and

without pneumonia. Some participants reported that when pulse oximeters are used, more children needing oxygen are identified and so are given the oxygen they need, and others reported that pulse oximeters can also help show when oxygen is not needed, or when to stop giving oxygen. Similar findings are documented elsewhere: Mwaniki et.al.(2009) found that if pulse oximeters had not been used with the Kenyan children in their study, 20% of those without hypoxemia would have been unnecessarily given oxygen. Moreover, the WHO's Recommendations for Management of Common Childhood Conditions states that a benefit of pulse oximeter use is that it results in oxygen conservation.

Oxygen is expensive. In Mwaniki et.al.(2009)'s study in Kenya, researchers estimated that a child on oxygen at 1 litre per minute cost US$6-14 per day. Perrelet et.al.(2004) reported that oxygen therapy in a rural Senegalese hospital cost the equivalent of two nurses' salaries. Interview participants also reported that oxygen is expensive in their hospitals. A reduction in oxygen overuse (which may also lead to reduced hospital length of stay), could therefore reduce healthcare costs, representing an important opportunity cost for low-income settings where resources are scarce.

Oxygen is a life-saving treatment, and its provision can be crucial in improving child health outcomes, hence why the WHO's List of essential medicines includes oxygen.[Langley&Cunningham,2016; Graham et.al.2017; WHO,2017d] Thus Duke et.al.(2008) found that when improved oxygen systems were implemented in five Papua New Guinea hospitals, the risk of death for children with pneumonia decreased by 35%. Evidence also indicates that oxygen can be harmful if given to patients unnecessarily.[Martin&Grocott,2013; Maitland et.al.2017] Surprisingly lacking, however, is evidence demonstrating and quantifying the relationship between oxygen provision (necessary/unnecessary) and children's health outcomes.[Langley&Cunningham,2016; Gilbert-Kawai et.al.2014; Rojas-Reyes et.al.2014; Maitland et.al.2017]

Concerning pulse oximetry's health and care impacts more broadly, my systematic review [Enoch et.al.2015] (Chapter 2) suggests that pulse oximeter use with children at admission to hospitals may lead to reduced mortality rates (when combined with improved/adequate oxygen administration), reduced triage time, increased admissions for children with hypoxemia, and can also change physicians' perceptions of illness severity, and decisions to use particular tests and treatments. This systematic literature review also however highlights the lack of adequate good quality research in this area, and therefore the need for more research on the impact of pulse oximeter use at admission on children's health outcomes (See Section 7.5.1). Other studies examining pulse oximetry's impact during healthcare delivery (e.g. for monitoring, or in outpatient settings) have found that pulse oximeter use with children can lead to reduced over-hospitalisation risk [WHO,2012], increased unnecessary admissions [Quinonez et.al.2017], longer hospital length of stay (particularly for children with bronchiolitis) [Schroeder et.al.2004], and increased referrals [McCollum et.al.2016].

Summary, and towards a health system perspective

Box 7.2 shows the main topics of interest drawn from the integrated findings.

Box 7.2: The main points of interest that can be drawn from the consolidation of the dataset analyses and interview findings

Points which have also been found elsewhere in the literature

- Pulse oximeters are widely regarded amongst HCWs as important, and as useful for helping to determine whether to give oxygen
- Some HCWs would not use pulse oximeters with all children, even if there were no barriers to pulse oximeter use, due to a lack of training on when to use pulse oximeters and why, and the belief that the clinical picture is important over and above the pulse oximeter value
- There is a widespread perception across all hospitals that not enough pulse oximeters are available in the paediatric wards
- The repair process often takes a long time, a problem which is compounded by the issue that there generally are no audits of the medical equipment; broken pulse oximeters often therefore remain unusable for long periods, even months

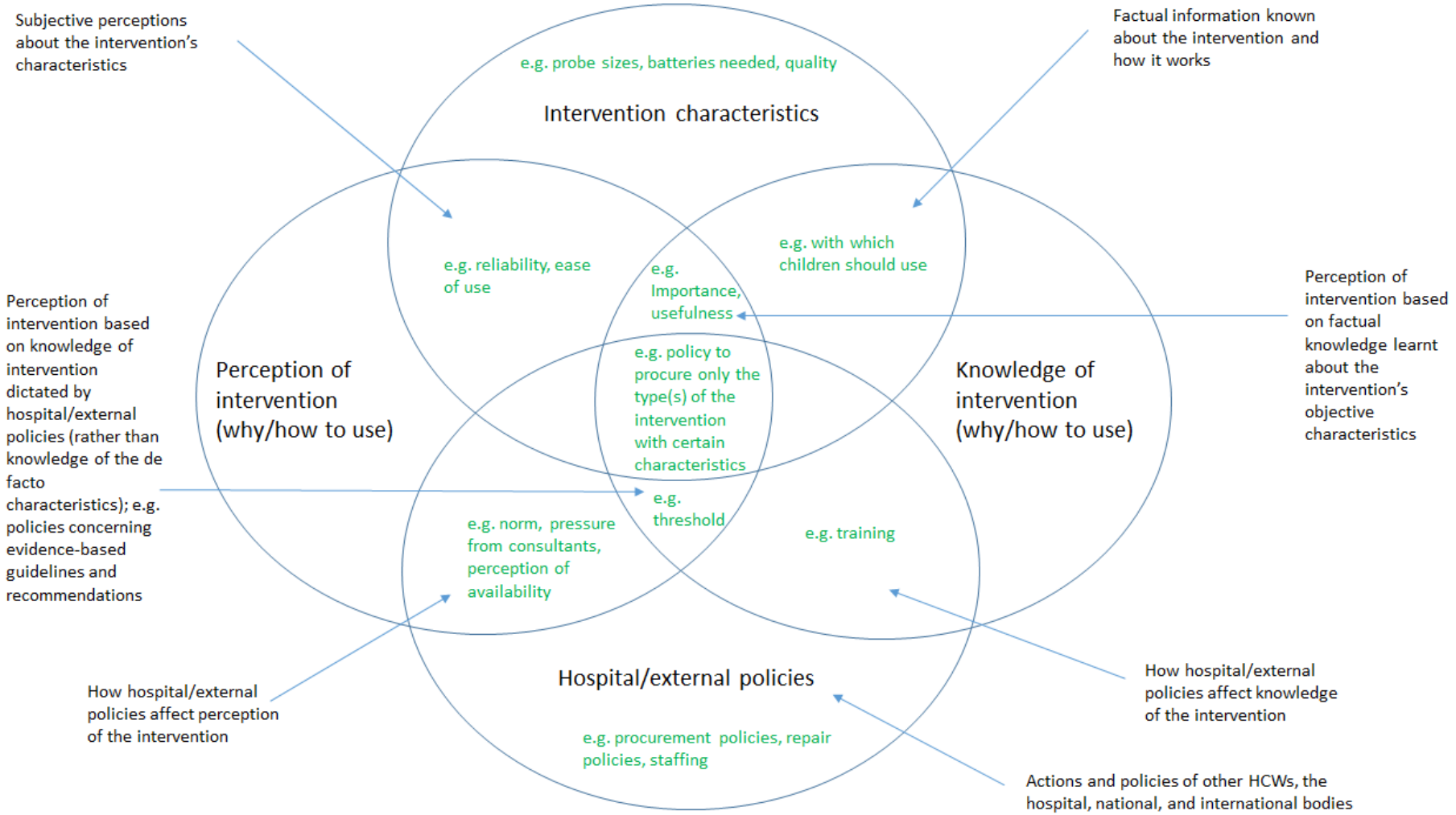
Points which have not previously been reported

- The procurement process at the hospitals often takes a long time, is unclear, and does not prioritize pulse oximeters
- HCWs almost universally claim to use the 90% threshold
- Because of a lack of training on how to use pulse oximeters and interpret their results, many HCWs do not know that children may need oxygen even if they do not have clinical signs indicating this. As a result of this and extensive experience with pulse oximeters that are / seem to be malfunctioning, some of these HCWs (particularly those of higher seniority) might doubt pulse oximeter readings when they contradict clinical signs
- There is a large variability in pulse oximeter use within and across hospitals over time; variability within hospitals (over time) seems to be largely due to pulse oximeters breaking and not being repaired quickly; variability across hospitals appears to be due to differences in the number of pulse oximeters available in each ward, and the presence or absence of a perceived norm, mainly determined by consultants, of using pulse oximeters with all children as a routine

Interestingly, there is considerable homogeneity across the setting, even though CIN hospitals vary in size (21-67 beds), admissions (1,300-3,400 yearly paediatric admissions), location (urban/rural, across 12 counties), socio-economic profile (20-65% of their catchment area populations live in extreme poverty), and pulse oximeter use (regarding when uptake began, average use, variability – see Section 3.2.3).[Ayieko et.al.2016]. Similar opinions and experiences were discussed across hospitals and HCW cadres in the interviews; the two exceptions were oxygen provision barriers, and the higher likelihood of a lack of confidence in pulse oximetry in HCWs of higher seniority.

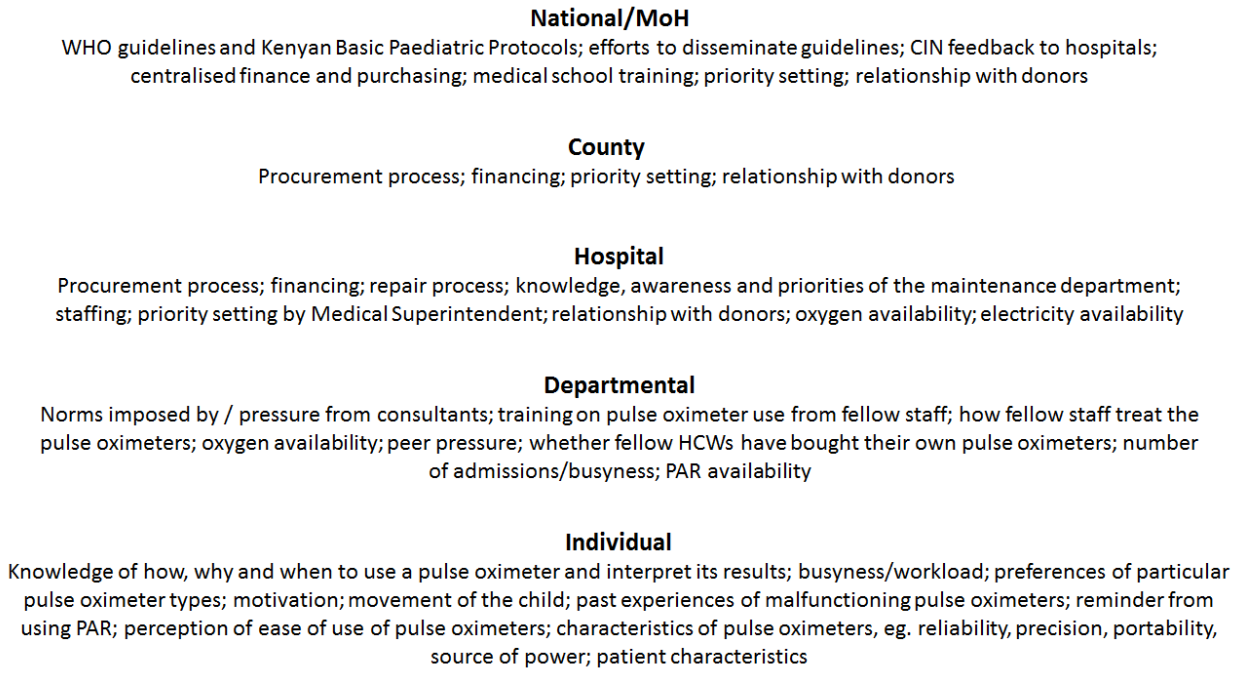
I now propose an alternative presentation of the results (Figure 7.1) with four intersecting themes: the interplay between the intervention's characteristics, the perception of the intervention (how and why to use it), the knowledge of the intervention (how and why to use it), and the hospital/external policies.

Figure 7.1: Alternative framework and visual representation of the factors impacting pulse oximeter use in Kenyan hospitals, according to the consolidated results of the dataset analyses and interview findings



The factors influencing the HCWs' opinions and experiences, and promoting or discouraging pulse oximeter use, are all interrelated, and operate across the levels of the health system hierarchy first introduced in Section 3.3.1; Figure 7.2 demonstrates these factors. A framework of constrictions on the health system, across the system levels, was created for the WHO's 2001 Commission on Macroeconomics and Health.[Mills,2014] My findings expand upon this framework through the addition of the intrinsic characteristics of available equipment (e.g. quality, appropriateness of type for context, etc.), and the HCWs' perceptions of these. What is noticeably lacking in the Kenyan hospital context is the community/household's influence, e.g. of parents. Pulse oximeter promotion programmes should work holistically across these levels, and doing so might impact other aspects of hospital care, e.g. procurement and repairs of other equipment, and HCW efficiency and motivation.

Figure 7.2: Examples of factors influencing pulse oximeter use that operate at each level of the health system hierarchy, according to the integrated findings from the analyses of the CIN data and interview findings; these factors and levels are interrelated and interact with each other



7.3 Methodological strengths, challenges, and limitations

7.3.1 Strengths

Conducting the systematic literature review was a transparent, effective way to identify previous research on the health impact of pulse oximeter use with children. Appraising this evidence and determining the research gaps assisted in identifying which areas to explore in the Kenyan hospital context. These areas were: pulse oximeter use variability, the situations when pulse oximeters are/are not used and why, whether pulse oximeters are appropriately used, and how their results influence care decision-making and why.

The CIN is a rare example of a clinical dataset containing a large number of variables examined from a large number of admissions in a low-income setting. This dataset is relatively high quality, due to the data collection system measures (electronic and manual) that monitor data quality, and periodic feedback given to hospitals on data recording quality.[Gachau et.al.2017]

The dataset analyses provided an understanding of the variation of behaviours across seven Kenyan hospitals, the frequency of these behaviours, and their distribution across the hospitals, which is useful information for understanding which behaviours are most in need of addressing, and how to target interventions to particular groups of HCWs. Such information can only be obtained from quantitative analyses of large clinical datasets. The sequential approach allowed the interview findings (spanning all CIN hospitals, with detailed investigation in four hospitals) to validate the dataset analyses findings. The interviews also led to a more comprehensive understanding of pulse oximetry in Kenyan hospitals by exploring explanations for the dataset analyses findings, and examining topics that the quantitative methods could not explore, e.g. HCW beliefs and pulse oximetry barriers. Furthermore, through the interviews I could

investigate HCW experiences and perspectives at hospitals with limited/no pulse oximeter use, to understand why pulse oximetry sometimes does not spread. In focusing on a specific setting (the CIN hospitals) through a 'case study' approach, I gained a more in-depth understanding of the topic within this context.

While I cannot conclude that my findings are representative of all low-income settings or even of Kenya, they provide insights into situations, experiences and perspectives likely to be relevant in Kenyan hospitals more widely, and other low-income settings. Table 7.4 compares CIN characteristics with those of Kenyan district hospitals more broadly. Other Kenyan district hospitals will likely face similar pulse oximetry barriers (and therefore my findings will likely be generalisable to these other settings), because e.g. they have many of the same characteristics as CIN hospitals as shown in Table 7.4, they are also resource-constrained settings, have the same procurement and repair systems and management structures as CIN hospitals, and the HCWs will have attended the same or similar medical schools. However, there is little data available on Kenyan hospital characteristics and therefore I cannot definitively conclude this.

Table 7.4: a comparison of characteristics of CIN hospitals vs. other district hospitals in Kenya

Measures	CIN hospitals	Other district hospitals in Kenya
Number of hospitals	14	70 (that provide internship training like the CIN hospitals)[i]
# of counties[ii]	12	47
Rural or urban	Rural and urban	Rural and urban
Population served by hospitals	Not known	250,000-600,000[i]
% of catchment area populations living in extreme poverty	20-65%[ii]	Not known
Healthcare provision is managed by[iii]	The County	The County
Hospital administrative team is led by[iv]	Medical Superintendent	Medical Superintendent

Paediatric admissions per year	1,300-4,100[ii]	Not known
Capacity	21-63 beds in paediatric ward[ii]	50-500 beds total in hospital[iv]
% of hospitals operating more than 100% bed occupancy	Not known	73%[v]
Ratio of nurses below age 60 to 10,000 population	Not known	0.1-9.7[vi]
Median patient/nurse ratio	Not known	11 (7-22) during the day; 26 (15-33) at night[v]
Average % of admissions who have pneumonia diagnosis	25-56%[vii]	46%[v]
Oxygen availability	Generally have access to oxygen, usually through concentrators / cylinders[viii]	Generally have access to oxygen, usually through concentrators / cylinders[i]
Paediatric Admission Record use	Used in all hospitals; used with 89% of children (range: 77-99%)	Used in 64% of hospitals; in those where used, is used with 43% of children (range: 13-100%)[v]

[i] English,2018; [ii] Ayieko et.al.2016; [iii] Wakaba et.al.2014; [iv] English,2013; [v] Gathara et.al.2015; [vi] Kenyan MOH,2015; [vii] This figure is only for hospitals included in the quantitative analyses; [viii] All semi-structured interview participants said they do not have problems accessing oxygen; several semi-structured conversation participants said they sometimes do not have enough oxygen for those children needing it (other barriers include broken/insufficient flow meters and splitters), see Section 6.3.4

An increasing literature exists on how to evaluate the external validity, applicability and transferability of healthcare research conducted on one group to other groups. Thus, in their systematic review, Burchett et.al.(2011) found 25 frameworks for this purpose. Their synthesis of these framework components resulted in an integrated framework with four categories (setting, intervention, outcomes, evidence). Evaluating my findings within this framework indicates that they could be applicable to hospitals in many low-income settings, due to similarities in criteria such as local need for the intervention (in many low-income settings, pulse oximeters are not available, and if available, not used), and evidence consistency (my findings are largely consistent with other studies (see Box 7.2 and Table 7.5)) As the authors state, more studies should be conducted evaluating the use of such measures of applicability in specific settings, e.g. Langhorne et.al.(2012) and Burchett et.al.(2013).

I expected that the semi-structured conversation participants may have felt more open to discuss controversial topics than in the semi-structured interviews, because the format was more informal, and the HCW conversations took place away from the hospitals (at the CIN meeting). However, participants in both formats seemed open to such discussions. The semi-structured conversations helped validate the in-depth interview results by showing that HCWs from the other 10 CIN hospitals have similar views and experiences as those in the four hospitals where interviews took place. By involving participants from a broader range of hospitals than the interviews, the conversations provided insights into several barriers only encountered in a subset of the hospitals, e.g. inadequate access to oxygen, and pulse oximeter absence.

I obtained further triangulation by emailing each interview participant with a list of their interview main points, asking if I had misunderstood anything, and if they wanted to add anything. Only one of the six HCWs who responded to this contact requested any changes, and these were minor. This process helped validate the results, while involving the participants in the research and emphasizing to them that their input is highly valued. A final analysis report will be sent to each participant.

In using the Integrative Model of Behavioural Prediction (IMBP) to frame the qualitative findings (see Sections 4.4 and 6.3) I could focus on factors influencing HCWs' intention to use a health technology, and factors affecting their ability to do so, the pathway of interest for this research. Also, the framework divided barriers into skill and environmental constraints, again relevant for pulse oximetry where skills/knowledge/training is key as are factors external to HCWs (e.g. determined by other staff, the hospital, County etc.). The model's only limitations were that the predisposing factors construct was not as relevant for this research as the other components, and that the model's behavioural pathway ends with the HCW performing/not performing the behaviour. Hence, I added the additional pathway component (see Section 6.2) examining how the behaviour is performed (e.g. whether pulse oximeters are used appropriately), because if

the behaviour is performed but not as recommended, the benefits might not occur. I propose that this extended model would be useful to others examining health technology adoption. The IMBP thus helped to frame the results; however, it was not used in the initial construct and theme extraction from the interviews, which instead were based entirely on the data. Using a different model may have altered which elements of the findings were emphasised. However, it is unlikely that the conclusions and recommendations would have been radically different as the core findings would have been the same regardless.

Other studies on health technology dissemination and uptake often essentially categorise HCWs as users/non-users at any timepoint. In contrast, I have expected HCWs' decision-making to vary with each child, and for HCWs to sometimes make different decisions, carry out different behaviours, or experience different barriers with different children. My findings support this approach.

7.3.2 Challenges

I used 'mixed-methods' guidance such as Tashakkori&Teddlie(2010), Creswell et.al.(2011), Padgett(2012), and Venkatesh et.al.(2016) to help guide my approach. There is as yet, however, no consensus or definitive guidelines on conducting mixed-methods research, including how to appropriately and effectively integrate each component's findings (see Section 1.3.5). It is thus difficult to standardize the methods, and to objectively evaluate their quality.

Furthermore, there are a range of difficulties associated with handling large datasets, and dealing with data collected from medical records, rather than purposively for the study. Section 3.8 elaborates on these. Consequently, during this thesis, I spent more than six months cleaning, organising and managing the dataset to prepare it for use in this research. This challenge is becoming more common with increasing use of 'big data' and 'real-world' datasets.[Cai&Zhu,2015; Chen et.al.2014; Jensen et.al.2012; Cohen et.al.2015; Wyber et.al.2015]

Another difficulty was deciding a multiple imputation process (there are various methods [van Buuren&Groothuis-Oudshoorn,2011]), and carrying it out. I used the multiple imputation by chained equations (MICE) approach [van Buuren&Groothuis-Oudshoorn,2011] because it is considered an effective and reliable method, and one can specify each variable's imputation model so continuous, binary and un/ordered categorical variables can all be included in the multiple imputation model.[White et.al.2011] The MICE approach has been used before with CIN data.[Gathara et.al.2017] There are also several statistical programmes that carry out multiple imputation in R; I chose 'mice' because it is a robust programme with various ways to specify multiple imputation process elements.[van Buuren&Groothuis-Oudshoorn] A major challenge was deciding how many imputations to run/determining when the imputations had converged, as there is no definitive guidance on how many imputations to run (given e.g. certain missing data thresholds) or how to determine when imputations have converged (see Section 3.10.5).

7.3.3 Limitations

I carried out an extensive search as part of my systematic literature review including through a range of databases of published studies, and a range of grey literature, such as the websites of relevant national and international health organisations (Appendix 2.1 contains a full list of search terms and methods). However, I did not search through any databases of Chinese published literature, or conduct a search in Google Scholar; it is possible that had I done so, I may have found more studies. I conducted the literature search with support and training from an information specialist, rather than it being conducted independently by two reviewers (see Section 2.2.4). However, other reviewers were involved in several aspects of conducting the review, for example: examination of the full texts for eligibility was completed by two reviewers, a second reviewer evaluated the risk of bias assessments, and the GRADE assessments were discussed by three reviewers.

Moreoever, the CIN dataset had several limitations. Thus, based on the CIN data collection Standard Operating Procedures, and on information provided by key informants involved in Kenyan hospital care or CIN data collection, it seems probable that oxygen use is under-reported in the dataset, because provision is sometimes not recorded in the medical records or only in the nursing cadex (where CIN data clerks do not look). Therefore, I cannot reliably estimate the proportions of children obtaining oxygen. I can still however compare relative levels of oxygen use across groups as the disparity between actual and recorded oxygen use is likely to be consistent across children; thus I am assuming it is a random documentation error.

Another dataset limitation was that sometimes the age variables were not consistent (see Section 3.8.1); this was not common however, and I devised a logic system to deal with this (see Appendices 3.6 and 3.7). Furthermore, diagnosing is subjective so some diagnoses may have been inaccurate. In particular, the literature describes difficulties in differentiating between pneumonia and malaria, severe cases of which both often present with fever and respiratory symptoms.[Bassat et.al.2011] Because of the dataset's nature, I was also not able to quantify the proportion of children who obtain oxygen that require vs. do not require oxygen, and the proportion of children who do not obtain oxygen that require it.

Furthermore, it would have been useful to have had data on additional measures: the admission time of day, as interviewees discussed disparities in care between night vs. day; nasal flaring and head nodding, which interviewees commonly mentioned; and HCWs' identity, so I could quantitatively analyse clinical behaviour by individual HCW and cadre.

Some argue that backwards stepwise regression can produce biased results where variables are identified by chance as influential/not influential.[Whittingham et.al.2006] However, I selected this method as there were many demographic and symptom variables I identified from previous research and key informants that could have influenced pulse oximetry or oxygen provision; it therefore was logical to include all initially and develop a best model using systematic variable

removal. This process' results were very similar to those produced through the bootstrap AIC method, suggesting that the model produced is robust for this dataset.

Another concern was that some odds ratios produced through logistic regression were very large (odds ratio for children with indrawing given oxygen: 2.68; OR children with pneumonia with pulse oximeter reading <90% given oxygen: 2.89; OR children without pneumonia with reading <90% given oxygen: 7.28; see Sections 5.6.2 and 5.7.3). However, when we calculate the risks of each of these events (e.g. of children with pneumonia and a pulse oximeter reading <90% being given oxygen), the values are relatively low (20%, 34%, and 22% respectively for the events listed above), which suggests that the odds ratios' over-estimation of the relative risk is unlikely to be substantial and so should not be problematic.[Davies et.al.1998] The potential exception is that of the children without pneumonia with a reading <90% given oxygen as the odds ratio of 7.28 is particularly large; however, the results discussion focused on broader concepts, e.g. that the odds ratio is positive and larger than that for children with pneumonia, rather than focusing on the specific value, so the discrepancy would not have influenced the interpretation.

I did not exclude children with very high missing data levels. While the multiple imputation process would have been less accurate for these individuals, I felt these children would contribute valuable data, and that their inclusion would not bias the results, as few children had very high missing data levels (<5% of children had >50% missing data), and all had less than 65% missing data.

Based on the literature, I had anticipated that procurement and repair issues, along with for example training, were likely to be barriers to pulse oximetry. [Elliott et.al.2006; Chohedri&Dahghani,2006; Orimadegun et.al.2011; Ginsburg et.al.2012; Ginsburg et.al.2014] I could have planned from the start to conduct further research into how the repair and procurement processes are organised in the Kenyan healthcare system and why they may not function effectively; this could have included document research and, within the qualitative

phase, conducting interviews with those involved in procurement and repair processes (e.g. hospital maintenance department staff, County finance officials, a range of Medical Superintendents) to explore their perceptions and experiences. This could have been valuable as such issues are common in health systems of low-income settings with wide-reaching implications, but little research explores this area. I did not however plan to do this investigation as I wanted to approach the qualitative research with an open mind to ensure the findings were drawn from the data rather than fitting the data into my hypotheses (see Section 4.10). In mixed-methods studies, the qualitative component is often conducted first, to inform quantitative data collection, but I chose to conduct the quantitative component first because the dataset I used for the quantitative analyses was collected prior to my research and so qualitative findings could not have informed data collection; furthermore, I could thereby design the HCW interviews to examine the reasons behind the quantitative findings and to explore the challenges to pulse oximeter use (see Section 3.3.1). However, if it had been feasible to conduct an additional qualitative stage before the quantitative work then I could have identified at an earlier point that procurement and repair issues were influential, and then could have planned for the aforementioned further research; alternatively, if it had been possible to have an additional research phase after the existing qualitative component then these areas could have been explored then. Unfortunately, it would not however have been practical to have an additional research phase within the scope and timeline of this thesis.

The semi-structured interview and conversation sampling did not enable detailed exploration in an explanatory sense of differences between Counties, or of senior management differences across Counties and hospitals; from the findings, I could only begin to identify how they might differ. Furthermore, I did not record the types of pulse oximeters used in the wards where interviews were conducted, so findings cannot be mapped to pulse oximeter type. Multiple HCWs asked if they could complete a paper questionnaire instead of speaking in an interview,

and declined to participate when told this was not possible; it could therefore have been useful to have included a questionnaire (qualitative and/or quantitative) as this may have captured views and experiences not otherwise included in this study.

I did not involve patient and public involvement (PPI) in the planning and data collection of the qualitative research. Thus, while none of the interviewees mentioned that parental perceptions influence their decision of whether to use a pulse oximeter, I could have asked them about this directly, and, more importantly, could have conducted interviews with mothers to understand their opinions of and experiences with pulse oximeters. This would have been particularly useful information given that mothers' perceptions of pulse oximeters have been shown to influence HCW decision-making in other settings [Enarson et.al.2008; Duke et.al.2009], and thus conducting these interviews could have provided a more multi-faceted understanding of the HCW-patient interaction. However, when planning the research I chose to focus on HCWs given that their behaviours, opinions and experiences are the topic of the thesis and relate to the data in the CIN dataset, and I did not feel it was practical, given resource and time constraints, to fully incorporate other groups into the research.

Some additional topics on the clinical use of pulse oximeters outside the research's scope that would have been interesting to explore include: differences in opinions and barriers for pulse oximetry at admission vs. for monitoring; pulse oximetry's impact on antibiotic provision; the perceived and actual issues concerning infection spread through contaminated probes (a topic raised by several interviewees), and methods used to/problems with cleaning probes; and differences in perceptions of, experiences with, and characteristics of different pulse oximeters. At the organisational level, it would have been interesting to examine the existing training systems, from medical schools to CME meetings.

Further limitations specific to each qualitative research approach are described below:

Observations

As each observation was for a short time, they only provided a snapshot of the HCWs who were present, rather than a full representation of the setting. Additionally, my direct observation might have influenced the behaviour of HCWs, who may have e.g. followed the Kenyan Basic Paediatric Protocols' recommendations, to give a better impression (the 'observer effect'). However, I used the observations to familiarise myself with the context, to help interpret data, rather than anything more broad or conclusive, and therefore these limitations should not have affected the results.

Semi-structured interviews

Due to resource, transport and time limitations, I had to limit the number of interviews to four hospitals, all within a few hours' drive from each other (although they were across four Counties); furthermore, I was restricted in when during the day I could visit the hospitals. This may have led to selection bias [Bernard,2011], in that participants may have differed from HCWs at other hospitals/on other shifts, and restricted my participant diversity. However, I compensated for this by carrying out semi-structured conversations with HCWs from 10 other hospitals.

The participants may not be representative as recruitment was determined by which HCWs agreed to be interviewed; those who agreed might have had different patterns of pulse oximeter use, opinions and experiences, e.g. if those who agreed were less busy and so more likely to have time to use pulse oximeters (non-response bias [Sedgwick,2014]). Response bias [Sedgwick,2014] may also have been influential: HCWs may have claimed to use pulse oximeters more often than was true because they thought that is what I wanted to hear, particularly as I was conducting research for my DPhil (the deference effect [Bernard, 2011]), or to enhance their reputation (the social desirability effect [Bernard,2011]). Furthermore, none of the interview

locations were completely private, so HCWs may potentially have felt reluctant to criticize others, particularly their superiors; however, this is unlikely to have been significantly problematic as the participants selected the locations.

However, given these interviews aimed at capturing diverse opinions to enable in-depth understanding of pulse oximetry in this context rather than being statistically representative, it is reassuring that saturation was reached.

Semi-structured conversations

Apart from the conversations with the Medical Superintendent and Procurement Officials which took place in their hospitals, the semi-structured conversations took place at a two-day meeting unrelated to this research, which was a gathering of paediatricians, MOs, nurses and data officers from 14 CIN hospitals, to discuss assessments and recommendations for care and recording of medical data. The likelihood of response bias concerning pulse oximetry benefits may have been elevated because guidelines and recommendations on paediatric care delivery were discussed at this meeting. Responses concerning use levels and barriers are unlikely to have been affected though, as these are based on personal experience, which is distinct from the guidance shared in the meeting.

Finally, if more information was available on the characteristics of hospitals across Kenya (see Table 7.4), on oxygen availability specifics, staffing, etc. from Ministry of Health data or research studies, then I could more effectively evaluate the generalisability of the findings of this thesis.

7.4 Implications for practice

My findings are applicable to the CIN dataset hospitals, but might also be relevant for programme planners in other low-income settings interested in increasing pulse oximetry.

Increase the supply of pulse oximeters and oxygen

Clearly more pulse oximeters are needed in these wards. A common suggestion is that there should be at least one pulse oximeter for each room of the paediatric ward. There should also be a consistently adequate supply of oxygen and associated equipment, e.g. flow meters.

The type of pulse oximeter(s) to purchase (or to accept as a donation) should be considered carefully, as there are a range of pulse oximeters with varying characteristics. Reliability and precision should be priorities, and power source (i.e. electricity availability, battery supply) should be considered. HCWs should have the option to request the pulse oximeter type that best suits their clinical situation, e.g. large stand-alone monitors displaying measures in addition to oxygen saturation vs. small, portable forms. Crucially, probes of various sizes (for newborns, infants, young children, older children) should be available with each pulse oximeter.

Improve the repair and procurement processes

It is not however enough to tackle the immediate supply problem, as is often done particularly by donors. Ensuring the repair and procurement processes are more efficient and transparent is also critical as this will enable a steady and sustainable availability of pulse oximeters and other equipment, allowing HCWs to perform care unabated. Thus, the process by which County officials and/or Medical Superintendents decide which equipment to fund should be more transparent, and there should be more effective communication channels for HCWs to explain why particular equipment is important and necessary. Furthermore, adequate funding should be allocated for medical equipment procurement (including for spare parts and e.g. batteries) and repairs. To improve the repair process, the maintenance department should be properly trained on how to examine and repair each device. Moreover, the maintenance department should have an inventory of all hospital equipment, have spare parts available in anticipation of equipment breaking, and carry out periodic audits to monitor whether equipment is malfunctioning. HCWs

and other hospital staff (e.g. administrators, maintenance department) should be fully aware of the repair and procurement process steps, and who is responsible for which steps.

Provide more training on a) how to use pulse oximeters, b) why it is important to use pulse oximeters with all children at admission, and c) how to interpret pulse oximeter results

Periodic training for HCWs of all cadres and experience levels could support pulse oximetry; training should include:

- Training sessions on how, when and why to use and interpret pulse oximeters: this can be done in a/multiple CME session(s) focusing on pulse oximetry[17]

- Reminders of this information: e.g. through ensuring the PAR is always used, and by sticking a/multiple chart(s) with this information on the ward wall[18]

- Sensitisation of pulse oximetry as routine: consultants can emphasise during ward rounds the need to always use pulse oximeters at admission, and HCWs can emphasise this to their colleagues at shift handovers[19]

These recommendations can be used by health administrators, hospital and governmental department leaders, policy decision-makers, and programme planners, in these 14 Kenyan hospitals, the wider Counties, the Ministry of Health, and in other low-income settings, to design effective programmes to increase pulse oximeter use with children at admission to hospital, and

[17] Providing training through CMEs was a common suggestion by interviewed HCWs. Irimu et.al.(2014) describe how CMEs can be effectively used to provide training in Kenyan hospitals.
[18] These were suggestions made by the interviewees; also, the literature supports the use of reminders for altering clinician care behaviour [Cheung et.al.2012; Flodgren et.al.2016; Pantoja et.al.2017; Ivers et.al.2012]
[19] These were common suggestions made by the interviewees when they were asked about how training could be most effective, and particularly how pulse oximeter use can become a routine

thereby increase the chance of prompt and effective treatment, potentially leading to decreased mortality rates, in line with the Kenyan national health plans and the Sustainable Development Goals. The potential for health outcome improvement in children with pneumonia is particularly encouraging given that almost half of children in the CIN hospitals have pneumonia (see Section 5.2), and this is the leading cause of death in children aged one month to five years worldwide.[Liu et.al.2016] Furthermore, in supporting effective treatment delivery, increased pulse oximeter use might also lead to hospital cost-savings. As discussed in Sections 2.4 and 7.5.1, more research is however needed to evaluate the effect of widespread pulse oximeter implementation on patients, facilities and resources, including unintended outcomes.

7.5 Further research, and implications for the broader diffusion of health technologies literature

7.5.1 Further research needed on pulse oximeter use in low-income settings

My findings indicate that further research is required in the following areas:

- How pulse oximeter use with children at admission to hospitals improves health outcomes, e.g. mortality, morbidity, and hospital length of stay
- How the procurement and repair processes (for pulse oximeters and other equipment) are organised and the ways in which they may not function effectively; how health systems can be supported to develop technology procurement/management programmes to make purchase and repair more effective and (cost-)efficient by operating at scale to negotiate contracts and build skills
- What oxygen saturation threshold, if any, should be used for deciding whether to give children oxygen, and in what clinical conditions, e.g. the most effective balance between

aiming to identify the largest proportion possible who need oxygen, while limiting the number who are given oxygen unnecessarily (wasting resources)

- The health outcomes of permitting lower oxygen saturation levels than normally recommended, particularly in less sick children
- The relationship between pulse oximetry and increased oxygen use in children who need oxygen, and the relationship between pulse oximetry and decreased oxygen use in children who do not need it
- How oxygen improves health outcomes; how giving oxygen to children unnecessarily can detrimentally impact their health, if at all; how these associations are related to different oxygen provision levels
- Mothers' perceptions of and experiences with pulse oximeters, and how these may affect HCW decision-making
- How pulse oximeter use affects antibiotics provision
- The precision, accuracy and reliability (real and perceived) of different pulse oximeter brands/types
- HCWs' perceptions/preferences of particular pulse oximeter types
- The cost effectiveness of pulse oximeter use/how pulse oximetry affects resource use (costs associated with oxygen and other treatments, extended or reduced hospital stays, procurement and maintenance of pulse oximeters, etc.)
- How the health and cost implications of pulse oximetry vary depending on the level of pulse oximeter use (e.g. rather than assuming there will be 100% availability and use)
- Whether following the above recommendations leads to increased pulse oximetry, improved health outcomes, and cost-savings, as predicted
- Pulse oximeter use and barriers beyond the admission event

- The potential for multicomponent diagnostic tools that measure oxygen saturation concurrently with other vital signs (which are also often missing in medical records)
- Oxygen availability in low-income settings, and barriers to use

7.5.2 How this research fits in with the diffusion of health technologies literature

In Chapter 1, I discussed factors the diffusion of health technologies literature presents as influencing dissemination and uptake. Table 7.5 lists these and indicates which were influential for pulse oximetry in Kenyan hospitals.

Table 7.5: Factors that influence health technology dissemination and uptake according to the literature, and whether relevant in the context of this research [Rogers,1995; WHO,2010; Pai et.al.2012; Free,2004; Palamountain et.al.2012; Denis et.al.2002; and others, see Section 1.2]

Framework constructs	**Factor categories**	**Specific factors**	**Whether relevant in study context**	**Explanation of relevance in context**
Perceptions of the technology	The technology's characteristics	Basic characteristics	√	How it is operated, its role in helping with oxygen provision decisions, etc.
		Scientific evidence	X	There is limited scientific evidence on this topic, and HCWs are not aware of the evidence that there is (e.g. of conditions in which a pulse oximeter reading would be the only way to identify hypoxemia)
		Acceptability and compatibility	X	No problem with compatibility within the cultural and organisational context; no need to / way to adapt it
		Perceived characteristics	√	HCW perceptions of pulse oximeters' ease of use, reliability, purpose, etc.
	Influence of colleagues and guidance	Colleagues and peers	√	Role of encouragement / pressure from consultants and colleagues
		Opinion leaders	√	The CIN leaders who provide feedback to the CIN hospitals are opinion leaders whose views and recommendations on care are trusted
		International agencies	(√)	Only relevant in so far as the WHO guidelines helped to inform the Kenyan Basic Paediatric Protocols and the work of the CIN
		Guidelines	√	Kenyan Basic Paediatric Protocols
		Feedback	√	Feedback from CIN and feedback from consultants

Characteristics of those who do or do not use the technology	HCWs' preconceptions, beliefs, opinions, attitudes, and knowledge	Previous experiences	X	Previous experience of other tools does not seem relevant
		Attitudes	√	Attitudes concerning the need to implement guidelines, the severity of the problem of hypoxemia, etc influence HCWs' likelihood of using pulse oximeters
		Which sources trust and prioritize	√	HCWs' trust of their perceptions of pulse oximeter unreliability over national guidelines leads to uncertainty about low pulse oximeter results
	How technology use influences the HCW's role	Role or workflow	√	HCWs like that pulse oximeters make their work easier; but when there are not enough pulse oximeters, a HCW who wants to use one may need to spend time searching for the scarce oximeter(s), which disrupts workflow
		Inadequate time	√	HCWs are less likely to use a pulse oximeter when busy (especially if they would need to go find/retrieve it first)
		Reputation / social status	X	Pulse oximeter use does not seem to be associated with reputation / social status
Factors relating to the context where the technology has been implemented	Health facility characteristics	Facility's structure and characteristics	√	Disorganisation of the procurement process and relationship between hospital and County
		Management of the health facility	√	The health facility's management of the procurement and repair processes are a major barrier
		Facility's interaction with other facilities	√	Competition with other hospitals because of CIN feedback
	How the technology fits within the context of the facility	Cost and resource use	√	Decisions concerning funding of procurement
		Health facility policies	X	There do not seem to be policies at the hospital level that influence pulse oximetry
		Supply	√	Inadequate supply of pulse oximeters is a major barrier to pulse oximeter use

		Storage	X	Pulse oximeters do not seem to generally be stored in inaccessible places
		Repairs and spare parts	√	A slow repair process results in HCWs being without broken pulse oximeters for long periods of time, another major barrier
		Infrastructure	X	Not relevant in this context
	How technology implementation was planned and carried out	Training	√	Insufficient training on when, why and how to use pulse oximeters and interpret their results leads to HCWs choosing not to use them, using them incorrectly, or misinterpreting their results
		Monitoring of quality	√	Lack of regular equipment audits results in extended time before malfunctioning pulse oximeters are repaired; a lack of monitoring of how HCWs use pulse oximeters leads to some unknowingly misusing them and so obtaining inaccurate results; both of these also lead to deterioration in perception of reliability and trust in results
		Involvement of stakeholders	√	HCWs do not seem to have been involved in the implementation process, pulse oximeters were simply introduced
		Trialability	(√)	HCWs can trial using a pulse oximeter before starting using it as a routine. One could argue that this is relevant when considering how some HCWs are uncertain of low pulse oximeter results, as if when a HCW is trialing an oximeter, they see it malfunctioning or giving results that contradict clinical signs, they may mistrust oximeter results going forward and therefore may ignore them.
		Observability	√	The fact that HCWs can observe others using a pulse oximeter before using it themselves is an advantage in that it allows for HCWs who have not been trained in pulse oximeter use to learn by watching others; but it is perhaps also a disadvantage

				because this may lead implementers to think there is no need to provide formal training on pulse oximetry
		Communication	√	Communication on the importance of pulse oximetry has led to widespread awareness of this; but a lack of communication of how, when and why to use pulse oximeters and their results has resulted in insufficient/inappropriate pulse oximeter use
		Funding	√	It seems that not enough funding may have been allocated for pulse oximeter / medical equipment supply, maintenance, repairs, implementation etc., thus contributing to inadequate procurement and repair processes and insufficient training

7.5.3 Further research needed on diffusion of health technologies

This thesis has identified a range of areas in which more research is required on the broader topic of health technology diffusion, particularly in low-income settings. For example:

- How individual HCWs make different decisions or face different barriers at different stages of the care process, with different children, and over time; HCWs should not be simply categorised into users/non-users
- How health technologies are used once they have spread, e.g. are they appropriately used
- How procurement and repair processes are organised, can act as barriers to health technology use, and can be improved
- How factors which promote, enable or discourage health technology uptake/spread operate at different health system hierarchy levels, how they interrelate, and how changing one influences another
- More long-term quantitative evaluations of adoption
- The political and economic components and implications of attempts to improve health technology dissemination
- How health technologies spread on a large scale e.g. across a country or region
- The sustainability of efforts to promote health technology dissemination, including how to reduce dependence on donors
- How changes can be made at the health system level to improve the dissemination process of all health technologies, not only individual technologies

Chapter 8: Conclusion

Half of the world's child deaths could be prevented by low-cost, effective interventions that already exist. One of these is pulse oximeters, the widespread implementation of which could lead to hundreds of thousands fewer yearly child deaths.[WHO,2017a; Floyd et.al.2015] And yet, such technologies are often not available in low-income settings, and even if available, are inconsistently used.

This thesis examined pulse oximeter use in low-income settings with a case study focusing on 14 Kenyan hospitals. I conducted a systematic literature review to determine the health impact of using pulse oximeters with children at admission to hospital; quantitative analyses of 28,000 child admissions to seven Kenyan hospitals, to understand with which children pulse oximeters are used, and pulse oximetry's impact on treatment decisions; and qualitative interviews with 30 staff from 14 Kenyan hospitals, to explore why HCWs use pulse oximeters with particular children and in particular situations rather than others, why pulse oximeter use influences particular treatment practices, the barriers to pulse oximeter use, and why pulse oximetry varies between and within Kenyan hospitals over time.

I found that, while the literature on health implications of pulse oximeter use with children at admission to hospital is scarce, there are indications that pulse oximeter use can decrease child mortality rates (when implemented alongside other oxygen provision improvements), decrease time spent in emergency department triage, increase admission rates for children with hypoxemia, and alter HCWs' decisions concerning illness severity and treatment provision. In the Kenyan hospitals I examined, I found that, while many HCWs agree that they should use pulse oximeters with all children, they often cannot do so, particularly because of insufficient pulse oximeter availability, due to inefficient and confusing procurement processes preventing

adequate supply of pulse oximeters and associated spare parts and batteries from being obtained, and/or because repairs take so long that HCWs are left without pulse oximeters for long periods when they break. Insufficient training on how, when, and why to use pulse oximeters and interpret their results has led to some HCWs not knowing with which children they should use pulse oximeters and why; some HCWs not being able to correctly use pulse oximeters (sometimes without knowing it); and many HCWs doubting pulse oximeter results that contradict clinical signs, sometimes resulting in children not obtaining necessary oxygen. When HCWs use pulse oximeters, they are most likely to use them with children who have respiratory symptoms or are not alert, and they use pulse oximeters at admission mainly to help with deciding which children need oxygen. Differential pulse oximetry between hospitals is most likely due to differences in pulse oximeter availability and in emphasis on pulse oximeter use by senior clinicians, while variation in pulse oximetry over time within hospitals is likely caused by fluctuations between when pulse oximeters are fully functioning vs. waiting to be repaired. There is often good awareness of national/international pulse oximetry guidelines, but these are often not followed, through choice or inability. My findings therefore suggest that whether a particular HCW uses a health technology, e.g. a pulse oximeter, with a particular child depends on an interaction between the intervention's characteristics, the HCW's knowledge of the intervention, the HCW's perception of the intervention, and the hospital/external policies.

This thesis shows the strengths of using a 'mixed-methods' approach and conducting case studies in implementation science, namely the opportunity to obtain an in-depth and holistic understanding of a local context, with implications for similar settings. Moreover, it demonstrates that large datasets of 'real-world' data collected in low-income settings, such as the Clinical Information Network dataset used in this research, are a valuable resource for evaluating and improving health interventions and care quality.

The goal of pulse oximeter promotion is for HCWs to as a routine obtain an accurate pulse oximeter reading for every child at admission, and for this reading to be appropriately interpreted and acted upon. Based on my findings and interviewees' suggestions on how best to promote pulse oximetry in their wards, I make the following recommendations, largely to be undertaken by the management of the involved hospitals and their paediatric wards, working with County officials, HCWs and others; these recommendations are also useful for those planning pulse oximeter promotion programmes elsewhere in Kenya or other low-income settings:

Hospital management should work with HCWs and County officials to ensure enough pulse oximeters, oxygen, and associated equipment (e.g. flow meters) are obtained for each paediatric ward, and better tools for helping managers with such planning could be helpful. These pulse oximeters need to be accurate and reliable forms, and appropriate given local contextual factors e.g. presence/absence of reliable electricity. HCWs should be consulted on which type to purchase as they know what is appropriate for their ward. Hospital management needs to ensure that donated pulse oximeters also have these characteristics; County officials, the Ministry of Health, and international health organisations such as the World Health Organization can put pressure on donors to adhere to these requirements. Crucially, sufficient probes must also be available in appropriate sizes for babies and children of every age.

However, to ensure a steady and sustainable supply of pulse oximeters and other equipment in the long term, hospital management and County officials should also make their repair and procurement processes more efficient. To work towards achieving these changes, global partners could collaborate with governments in capacity-building and helping to adapt systems and processes based on evidence from similar settings. The procurement and repair processes should be transparent and clearly explained to all hospital staff so all fully understand how to request new equipment or repairs and who is responsible for which steps. Sufficient funding

should be allocated for these processes. Furthermore, hospital management should ensure the maintenance department staff are fully trained in repairing the hospital equipment, and that they carry out regular equipment audits.

Those leading the paediatric ward should ensure sufficient training is provided on how, when and why to use pulse oximeters and interpret their results. Such training should be periodic and provided to all HCWs. It is most likely to be effective if it contains a combination of components involving formal teaching (e.g. in Continuing Medical Education Sessions), reminders (e.g. through using the Paediatric Admissions Record, having information charts on the wall), and encouragement from fellow HCWs (e.g. during ward rounds and shift handovers).

Carrying out these recommendations can also improve the availability and use of other health technologies, and enable HCWs to perform their roles more effectively and efficiently. Increasing pulse oximetry in these hospitals and other low-income settings could improve diagnosis and treatment speed and accuracy, potentially reducing child mortality rates, in line with national health plans, and the Sustainable Development Goals.

This research also has implications for the wider diffusion of health technologies literature. Thus, based on my findings, I also recommend that health technology interventions prioritize supply, repair, and training in their programmes; not categorize HCWs as users/non-users but rather realise decisions and barriers may differ for each HCW-patient interaction; and ensure they consider and evaluate not only whether technologies are used, but also whether they are used appropriately.

Moreover, I recommend that further research is conducted on the impact of increased pulse oximetry on health outcomes and resource use; which, if any, pulse oximeter result threshold should prompt oxygen provision; the repair and procurement processes in health systems of low-income settings, and how to improve these; the relationship between oxygen use and

health outcomes; the accuracy, reliability, and preference of different pulse oximeter types; and barriers to oxygen provision in low-income settings. More broadly, more research is needed on the factors across the health system hierarchy levels that promote, enable, or discourage the spread, uptake and appropriate use of other health technologies (particularly other 'simple' diagnostic tools), including across large scales such as countries or regions, and the health, political and economic implications.

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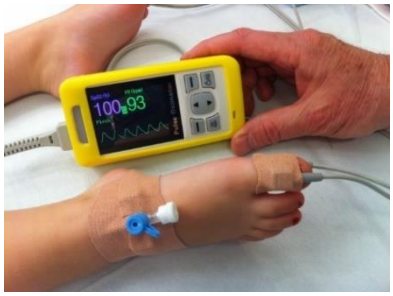
Appendices

Appendix 1.1: Images and diagrams of a selection of pulse oximeters

Handheld pulse oximeter, with probe that attaches to finger:

[Ghana Broadcasting Corporation,2017]

Handheld pulse oximeter, with probe that attaches to toe:



[Lifebox,n.d.a]

Probe that attaches to foot (designed to be usable with children of any size):

[Lifebox,n.d.b]

Large table-top pulse oximeter monitor:

[Philips,n.d.]

Medium table-top pulse oximeter monitor:

[Masimo,n.d.]

Standalone monitor, which measures other vital signs in addition to pulse oximetry:

[Thames Medical,n.d.]

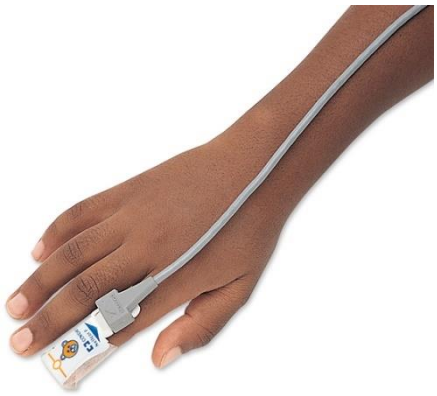
Pulse oximeter that delivers results to a smartphone:

[Amazon,n.d.a]

Simple finger pulse oximeter (generally for home use):

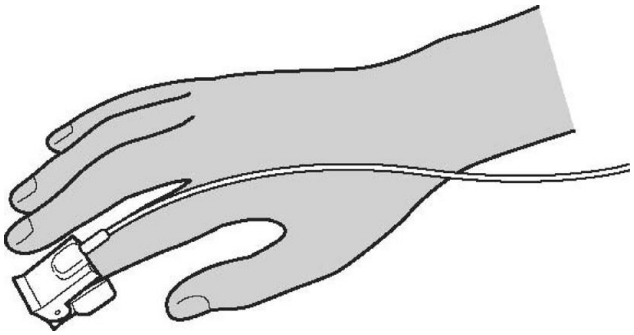
[Amazon,n.d.b]

Different types of finger probes:

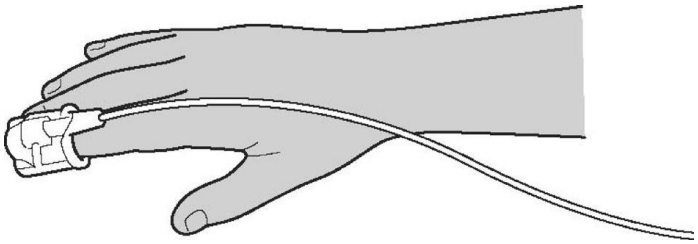


[Medtronic,n.d.]

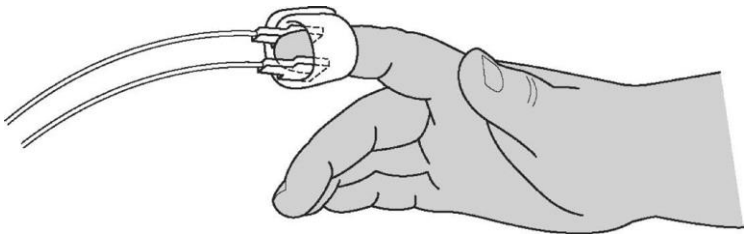
Hard plastic finger clip for adults



Soft rubber sensor probe



Y sensor probe



[WHO,2014b]

Appendix 2.1: Search terms and search methods

Database	Searches performed	Date	Notes
Dare	**1. [any field] "pulse oximeter" OR [any field] "pulse oximetry"**	January 7, 2015	The Dare tickbox was ticked for the search
Pubmed	1. (((“Infant”[Mesh]) OR “Child”[Mesh]) OR “Adolescent”[Mesh]) OR “Pediatrics”[Mesh] 2. (Newborn*[Title/Abstract] OR Neonat*[Title/Abstract] OR Baby*[Title/Abstract] OR Babies[Title/Abstract] OR Infant*[Title/Abstract] OR Child*[Title/Abstract] OR Kid*[Title/Abstract] OR Toddler*[Title/Abstract] OR Adoles*[Title/Abstract] OR Teen*[Title/Abstract] OR Boy*[Title/Abstract] OR Girl*[Title/Abstract] OR Paediatric*[Title/Abstract] OR Peadiatric*[Title/Abstract] OR Pediatric*[Title/Abstract]) 3. #1 OR #2 4. “Oximetry”[Mesh] 5. (“Pulse oximeter*”[Title/Abstract] OR “Pulse oximetry”[Title/Abstract]) 6. #4 OR #5 **7. #3 AND #6**	January 9, 2015	
Web of Science	1. TS=(“Pulse oximeter*” OR “Pulse oximetry”) OR TI=(“Pulse oximeter*” OR “Pulse oximetry”) 2. TS=(Newborn* OR Neonat* OR Baby* OR Babies OR Infant* OR Child* OR Kid* OR Toddler* OR Adoles* OR Teen* OR Boy* OR Girl* OR Paediatric* OR Peadiatric* OR Pediatric*) OR TI=(Newborn* OR Neonat* OR Baby* OR Babies OR Infant* OR Child* OR Kid* OR Toddler* OR Adoles* OR Teen* OR Boy* OR Girl* OR Paediatric* OR Peadiatric* OR Pediatric*)	January 13, 2015	In “All databases” and for all years

	3. #1 AND #2		
Cochrane library	**1. "pulse oximeter" OR "pulse oximetry"**	January 8, 2015	In "Title, Abstract or Keywords" "Cochrane reviews", "Other reviews" and "Technology assessments" tick boxes were ticked
Medion	**1. Pulse oximeter** **2. Pulse oximetry**	January 8, 2015	In "Topics"
WHO Global Health Library	**1. Pulse oximeter** **2. Pulse oximeter** **3. Pulse oximetry** **4. Pulse oximetry**	January 8, 2015	#1 and #3 were in "title" and in "regional"; #2 and #4 were in "subject" and in "regional"
Embase	1. Pulse oximeter/ or pulse oximetry/ 2. ("Pulse oximeter*" or "Pulse oximetry").mp. 3. ("Pulse oximeter*" or "Pulse oximetry").m_titl. 4. #1 OR #2 OR #3 5. (Newborn* OR Neonat* OR Baby* OR Babies OR Infant* OR Child* OR Kid* OR Toddler* OR Adoles* OR Teen* OR Boy* OR Girl* OR Paediatric* OR Peadiatric* OR Pediatric*).mp. 6. (Newborn* OR Neonat* OR Baby* OR Babies OR Infant* OR Child* OR Kid* OR Toddler* OR Adoles* OR Teen* OR Boy* OR Girl* OR Paediatric* OR Peadiatric* OR Pediatric*).m_titl. 7. #5 OR #6 **8. #4 AND #7**	January 14, 2015	-#1 was done by "mapping to subject headings" but not ticking "explode" -mp=title, abstract, subject headings, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword
Global Health	1. ("Pulse oximeter*" OR "Pulse oximetry").mp. 2. ("Pulse oximeter*" OR "Pulse oximetry").m_titl. 3. #1 or #2 4. (Newborn* OR Neonat* OR Baby* OR Babies OR Infant* OR Child* OR Kid* OR Toddler* OR	January 14, 2015	mp=abstract, title, original title, broad terms, heading words, identifiers, cabicodes

	Adoles* OR Teen* OR Boy* OR Girl* OR Paediatric* OR Peadiatric* OR Pediatric*).mp. 5. (Newborn* OR Neonat* OR Baby* OR Babies OR Infant* OR Child* OR Kid* OR Toddler* OR Adoles* OR Teen* OR Boy* OR Girl* OR Paediatric* OR Peadiatric* OR Pediatric*).m_titl. 6. #4 OR #5 **7. #3 AND #6**		
CINAHL	1. TI ("Pulse oximeter*" OR "Pulse oximetry") OR AB ("Pulse oximeter*" OR "Pulse oximetry") 2. TI (Newborn* OR Neonat* OR Baby* OR Babies OR Infant* OR Child* OR Kid* OR Toddler* OR Adoles* OR Teen* OR Boy* OR Girl* OR Paediatric* OR Peadiatric* OR Pediatric*) OR AB (Newborn* OR Neonat* OR Baby* OR Babies OR Infant* OR Child* OR Kid* OR Toddler* OR Adoles* OR Teen* OR Boy* OR Girl* OR Paediatric* OR Peadiatric* OR Pediatric*) **3. #1 AND #2**	January 14, 2015	

Note: the search(es) shown in **bold** is/are the one(s) from which results were taken

The websites of the following organizations were searched using the search terms 'pulse oximeter' and 'pulse oximetry' to obtain unpublished reports: the World Health Organization, the World Bank, USAID, Public Health England, the UK's Department of Health, NHS Evidence – NICE, PATH, Save the Children, Save the Children UK, MSF, Oxfam, UNICEF, the International Union Against Tuberculosis and Lung Disease, the British Lung Foundation, and the World Heart Foundation.

Appendix 2.2: Characteristics of Included Studies table

Study	Methods	Participants	Intervention	Outcomes
Anderson et.al. 1991	Non-controlled before-after study; illness severity score and management plan recorded before and after the physician obtained the child's pulse oximeter results	437 children who were all in the control group and then the intervention group; average age of 5 years and age range of 1 day to 17 years; Massachusetts, USA	Pulse oximeter results shown to physician after they had decided on illness severity score and management plan	-# and % whose illness severity score changed, and whether considered more vs. less ill after -# and % whose management plans changed, and whether more vs. less aggressive plan after
Choi & Claudius 2006	Non-controlled before-after study; time spent in ED triage was measured before and after pulse oximeters were introduced as a standard triage tool	159 in control group, 89 in intervention group; average age of 11 months and 8 respectively; Los Angeles, USA	Pulse oximeters were introduced into ED triage standard methods	Time spent in ED triage
Duke et.al. 2008	Non-controlled before-after study; mortality rates of children with pneumonia at 5 hospitals before and after pulse oximeters and oxygen concentrators were introduced	7161 in control group, 4130 in intervention group; children up to 5 years old; Papua New Guinea	Pulse oximeters and oxygen concentrators were introduced into 5 hospitals with training	Mortality rates
Maneker et.al. 1995	Non-controlled before-after study; management plan recorded before and after the physician obtained the child's pulse oximeter results	368 children who were all in the control group and then the intervention group; 16% were less than than 6 months old, 59% were 7 to 36 months old, 15% were 37 to 96 months old, and	Pulse oximeter results shown to physician after they had decided on management plan	-# and % of those with unexpectedly low SaO2 whose management plans changed, including whether oxygen therapy was added, and/or if

		10% were more than 96 months old; Ohio, USA		they were newly admitted -# and % of those with expectedly low SaO2 whose management plans changed, including whether oxygen therapy was added, and/or if they were newly admitted
Mower et.al. 1997	Non-controlled before-after study; management plan recorded before and after the physician obtained the child's pulse oximeter results	2127 children who were all in the control group and then the intervention group; ages ranged from birth to 17 years; Los Angeles, USA	Pulse oximeter results shown to physician after they had decided on management plan	-# and % of those with each oxygen saturation value who obtained new diagnostic tests, new treatments, new diagnoses, and/or were newly admitted

Appendix 2.3: Characteristics of Excluded Studies table

Study	Reason(s) for exclusion
Schroeder et.al. 2004	-retrospective case series -all children received pulse oximeter readings -pulse oximeter readings were not necessarily taken at admittance – they may instead have been used for monitoring later as part of treatment
Schuh et.al. 2014	-all children received pulse oximeter readings
Cunningham et.al 2015	-all children received pulse oximeter readings

Appendix 2.4: detailed summary of findings table

Pulse oximeters vs. no pulse oximeters to inform diagnosis and treatment (excluding operative surgical care)							
Population: newborns, children and adolescents aged up to 19 years Intervention: pulse oximeter readings Control: populations with no pulse oximeter readings Outcomes: mortality rates, morbidity, length of hospital stay							
Outcomes	**Overall outcome difference between control and intervention group**	**Number of participants by outcome (studies)**	**Specific study differences between control and intervention group [see Risk of Bias table for risk of bias assessments for each study]**	**Number of participants by study**	**Relative effect (with 95% CI)**	**Absolute effect (with 95% CI)**	**Quality of the evidence - GRADE**
Mortality rates	The introduction of pulse oximeters alone may lead to a reduction in mortality rates.	11,291 (1 – Duke et.al. 2008)	-Mortality rate changed from 4.97% to 3.22% (35% relative reduction) [for those admitted with a diagnosis of pneumonia] after pulse oximeters, oxygen concentrators and training introduced -Mortality rate changed from 5.53% to 4.1% (26% relative reduction) [for those > 1 month old admitted with any diagnosis] after pulse oximeters, oxygen concentrators and training introduced	11,291 32,335	RR: 0.65 (0.55, 0.77)	Reduction of 1.75% (1.01, 2.49) or 18 fewer deaths per 1000 patients	Very low[i]
Morbidity: -Assessed degree of illness	-When pulse oximeter results are obtained in the ED, the assessed degree	2564 (2 – Anderson et.al.1991; Mower et.al.1997)	-No difference (in children with diagnosis of 'well', 'minor orthopaedic injuries' or 'minor surgical injuries') after physicians received pulse oximeter results [Anderson et.al.1991]	83	n/a	n/a	Very low[ii]

-Diagnosis	of illness and the diagnosis for children may be different than if pulse oximeter results are not obtained. This is especially the case for children who do not have a diagnosis of 'well', 'minor orthopaedic injuries' or 'minor surgical injuries', and/or is more likely in children who have low SaO2 values.		-53% (of children with diagnoses that were not 'well', 'minor orthopaedic injuries' or 'minor surgical injuries') had a change after physicians received pulse oximeter results; 25% of these were assessed as more ill; 69% were assessed as less ill; direction of change was unknown for 6% [Anderson et.al. 1991] -diagnosis was changed for 8% of children (of those with SaO2<95%) after physicians received pulse oximeter results [Mower et.al.1997] -diagnosis was changed for 0.7% of children (of those with SaO2≥95%) after physicians received pulse oximeter results [Mower et.al.1997]	354 305 1822			
Length of hospital stay	The introduction of pulse oximetry into triage may decrease the	622 (3 – Choi & Claudius, 2006; Maneker	-Time spent in ED triage decreased from 4 hours 59 minutes to 4 hours 9 minutes (50 minutes less; a 17% decrease) after pulse oximeters	248	Mean difference : 50 minutes	17 fewer minutes spent in triage per	Very low[iii]

	average time children spend in triage and may increase the proportion of hypoxic children who are admitted.	et.al.1995; Mower et.al.1997)	introduced into emergency department triage [Choi&Claudius, 2006] -28% were admitted only after the pulse oximeter readings were revealed (out of children with unexpectedly low SaO2 (where low SaO2 defined as <92%)) [Maneker et.al.1995] -4% were admitted only after the pulse oximeter readings were revealed (out of children with expectedly low SaO2 (where low SaO2 defined as <92%)) [Maneker et.al.1995] -2% were admitted only after the pulse oximeter readings were revealed (out of the children with SaO2<95%) [Mower et.al.1997] -0.3% were admitted only after the pulse oximeter readings were revealed (out of the children with SaO2≥95%) [Mower et.al.1997]	46 23 305 1822	(3.76, 96.24) / n/a	100 minutes / n/a	
Secondary research question: treatment and manage-ment	When pulse oximeter results are obtained in the ED, the management plans for children may be different	2633 (3 – Anderson et.al.1991; Maneker et.al.1995; Mower et.al.1997)	-No difference (in children with diagnosis of 'well', 'minor orthopaedic injuries' or 'minor surgical injuries'] after pulse oximeter results received) [Anderson et.al.1991]	83	n/a	n/a	Very Low[iv]

	than if pulse oximeter results are not obtained. This is especially the case for children who do not have a diagnosis of 'well', 'minor orthopaedic injuries' or 'minor surgical injuries', and/or is more likely in children who have low SaO2 values, particularly if these are unexpectedly low.		-19% (of children with diagnoses that were not 'well', 'minor orthopaedic injuries' or 'minor surgical injuries') had a change after physicians received pulse oximeter results; 39% of these had more aggressive management after; 58% were managed less aggressively after; direction of change was not documented for 3% [Anderson et.al. 1991] -91% (of those who unexpectedly had low SaO2 (where low SaO2 defined as <92%)) had a change after physicians received pulse oximeter results; 90% of these had oxygen added [Maneker et.al.1995] -43% (of those who expectedly had low SaO2 (where low SaO2 defined as <92%)) had a change after physicians received pulse oximeter results; 90% of these had oxygen added [Maneker et.al.1995] -new diagnostic tests were ordered for 20% (of those with SaO2<95%) after physicians received pulse oximeter results [Mower et.al.1997]	354 46 23 305			

			-new diagnostic tests were ordered for 0.5% (of those with SaO2≥95%) after physicians received pulse oximeter results [Mower et.al.1997] -new treatments were ordered for 11% (of those with SaO2<95%) after physicians received pulse oximeter results [Mower et.al.1997] -new treatments were ordered for 1% (of those with SaO2≥95%) after physicians received pulse oximeter results [Mower et.al.1997]	1822 305 1822			

[i] Non-controlled before-after study: Study limitations – there is a high risk of bias as the Duke et.al.2008 study had a serious risk of bias, due mainly to the fact that oxygen concentrators and training were introduced into the study hospitals concurrently with pulse oximeters so it is not possible to determine how much of the change in mortality rates shown in the study was due specifically to pulse oximeter use; indirectness – the study was looking at the impact of the introduction of pulse oximeters and oxygen concentrators on mortality rates, rather than just the introduction of pulse oximeters alone; imprecision - only 1 study (and it did not report confidence intervals for the measure of interest); this outcome has therefore been downgraded from Low to Very Low.

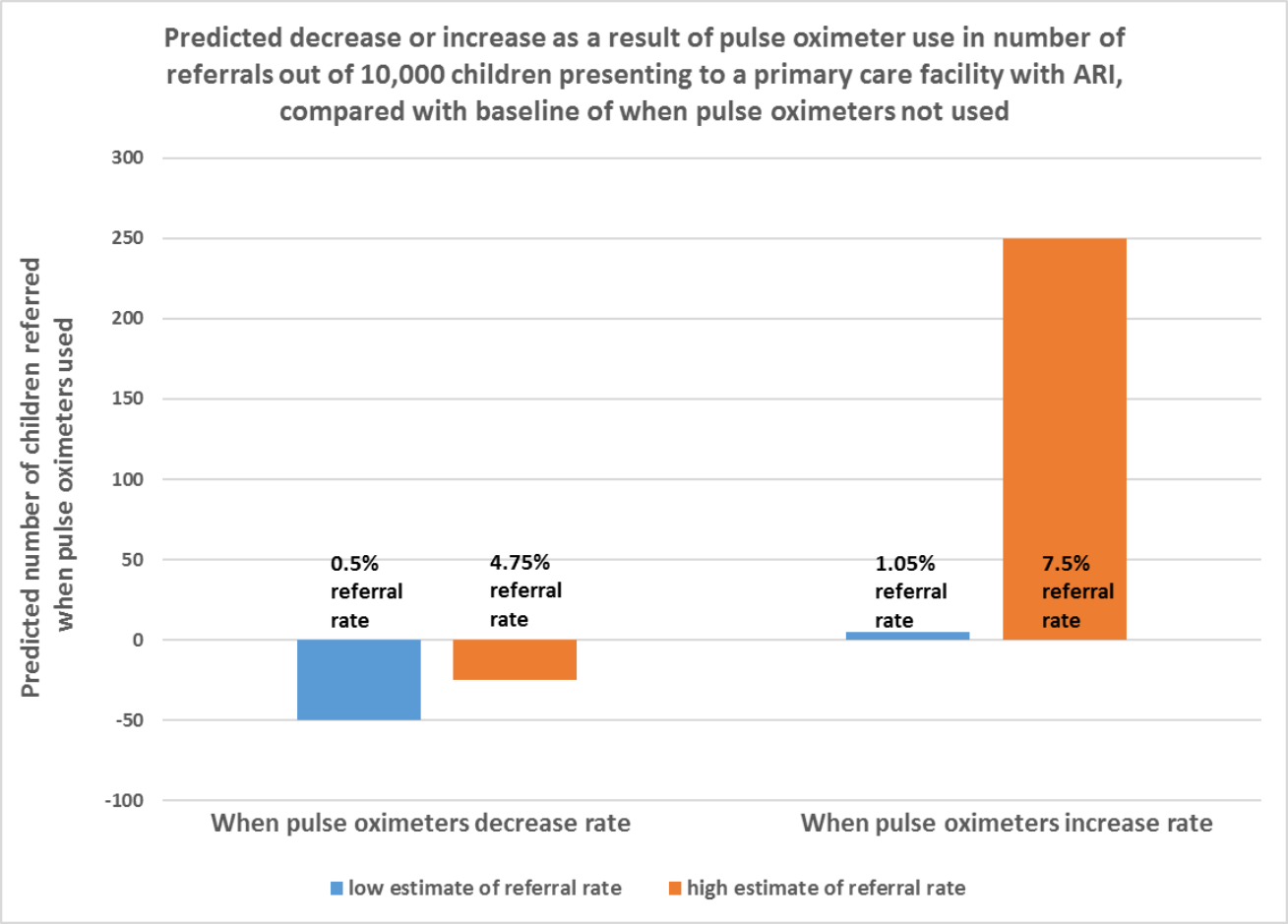
[ii] Non-controlled before-after studies: Study limitations – there is a high risk of bias as both of these studies had a serious risk of bias, because the physicians in both studies were aware of the intervention status of the participants and so may have been more likely to take the pulse oximeter results into account than had they received the pulse oximeter results during their initial evaluations; in addition the authors of Mower et.al.1997 excluded 20% of children who could have been included in the study, potentially affecting the results, and the authors of Anderson et.al.1991 excluded a subgroup of children from the analyses when it became evident that pulse oximeter results did not impact their management, so the study's results of pulse oximeter impact were exaggerated; indirectness – the changes in degree of illness and diagnosis shown in these studies are not actual changes in morbidity, they are changes in physicians' perceptions of morbidity; also both studies were looking at different sub-outcomes and different subgroups from each other, most of which were not directly relevant to, or only partially relevant to, the review; imprecision – only 2 studies (neither of which reported any confidence intervals); this outcome has therefore been downgraded from Low to Very Low.

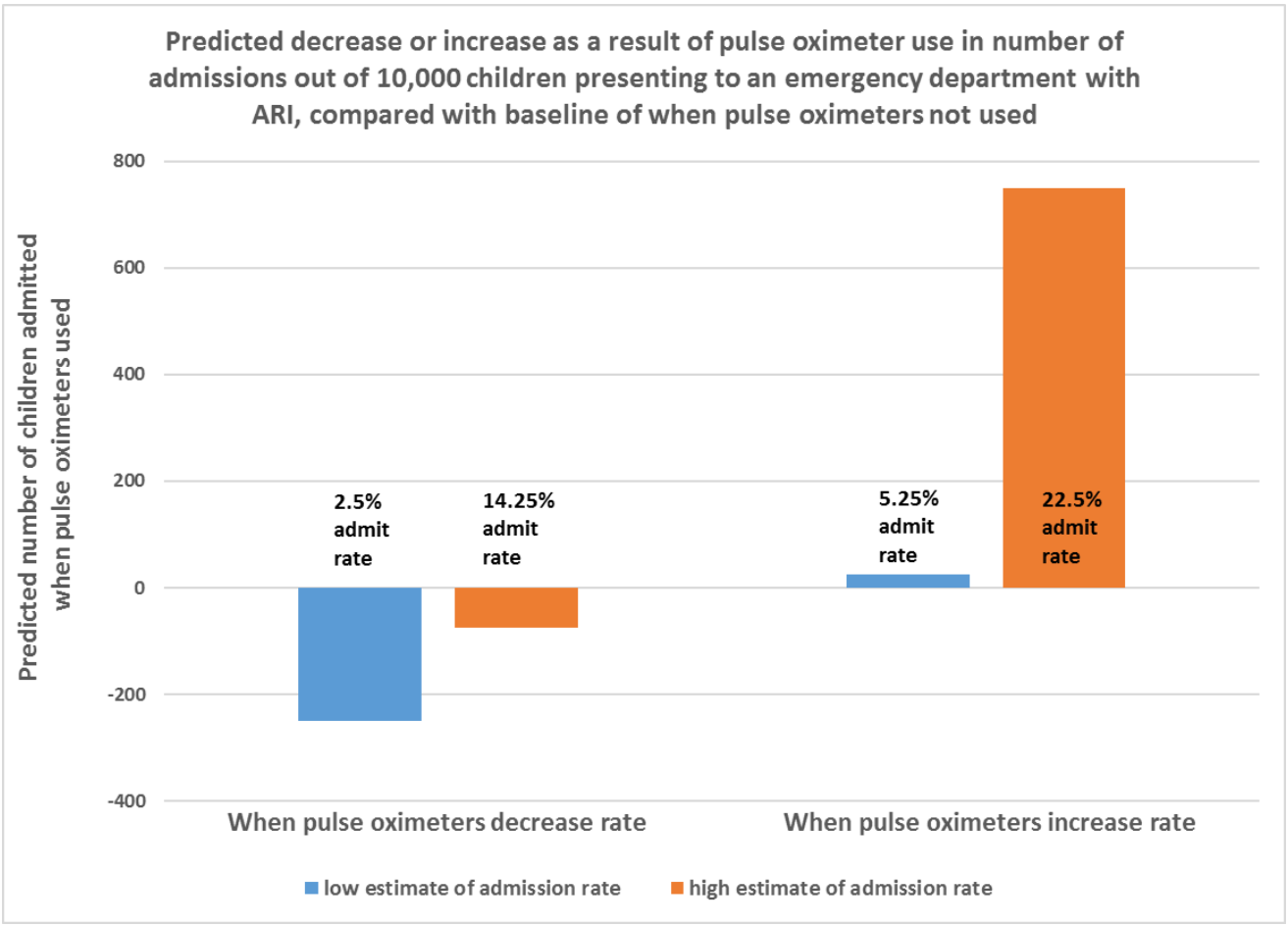
[iii] Non-controlled before-after studies: Study limitations – there is a high risk of bias as two of the studies had a serious risk of bias, because the physicians in both studies were aware of the intervention status of the participants and so may have been more likely to take the pulse oximeter results into account than had they received the pulse oximeter results during their initial evaluations; in addition 20% and 32% of potential participants were not included in the Mower et.al.1997 and Maneker et.al.1994 studies respectively, potentially affecting the results;

indirectness – the outcomes investigated in the three studies (length of stay in ED triage, and % admitted) are indirectly related to but not exactly the same as, the outcome of length of hospital stay; imprecision – only 3 studies (none of which reported any confidence intervals); this outcome has therefore been downgraded from Low to Very Low.

[iv]Non-controlled before-after studies: Study limitations - there is a high risk of bias as all three of these studies had a serious risk of bias, because the physicians in all three studies were aware of the intervention status of the participants and so may have been more likely to take the pulse oximeter results into account than had they received the pulse oximeter results during their initial evaluations; in addition 20% and 32% of potential participants were not included in the Mower et.al.1997 and Maneker et.al.1994 studies respectively, potentially affecting the results; also the authors of Anderson et.al. 1991 excluded a subgroup of children from the analyses when it became evident that pulse oximeter results did not impact their management, so the study's results of pulse oximeter impact were exaggerated; indirectness – the secondary research question considered the impact of pulse oximeter use on the proportion of children receiving oxygen therapy – only one of the studies actually reported the number of children in both groups who received oxygen therapy while the other two studies only reported results on outcomes that are related to oxygen therapy, by, like oxygen therapy, being examples of treatment and management; also all three studies were looking at different sub-outcomes and different subgroups from each other, most of which were not directly relevant to, or only partially relevant to, the review; imprecision – only 3 studies (none of which reported any confidence intervals); this outcome has therefore been downgraded from Low to Very Low.

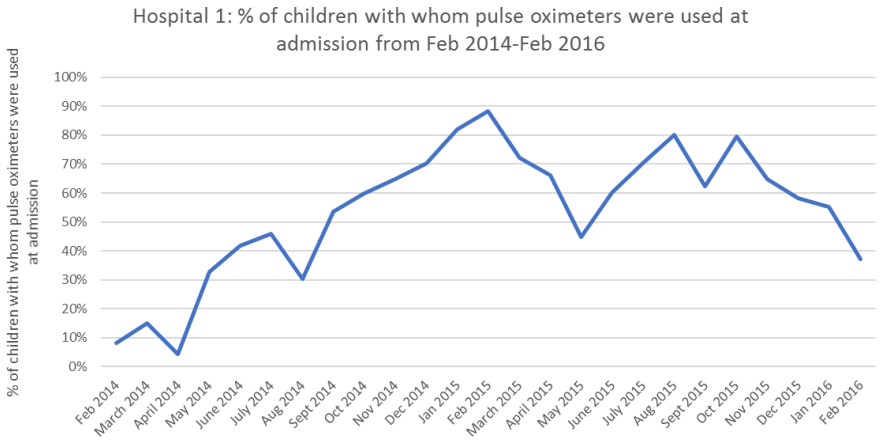
Appendix 2.5: Simple, hypothetical illustrations of introducing pulse oximetry into primary care or walk-in clinical settings illustrating the trade-offs that may be apparent in terms of increased or decreased referral or admission rates based on plausible (low and high) estimates of existing rates and true prevalence of hypoxemia

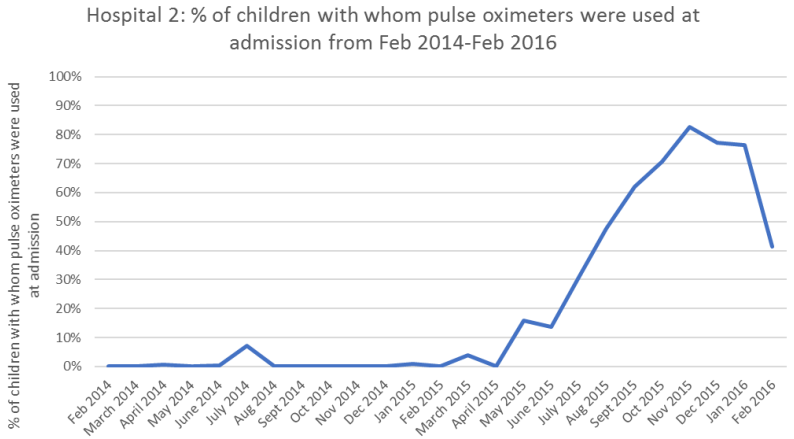


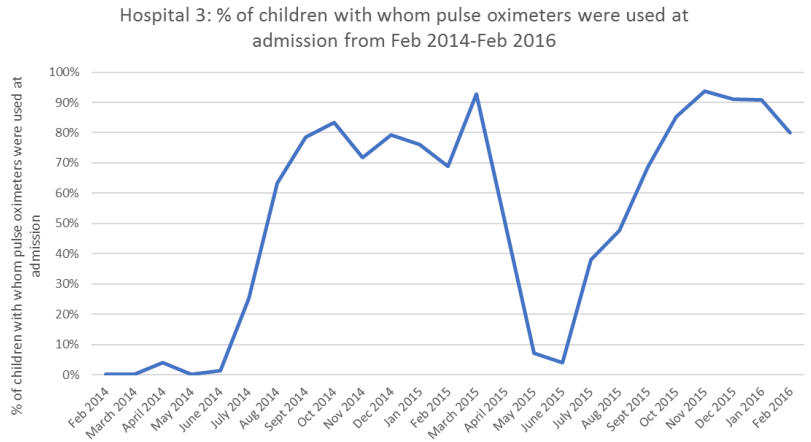


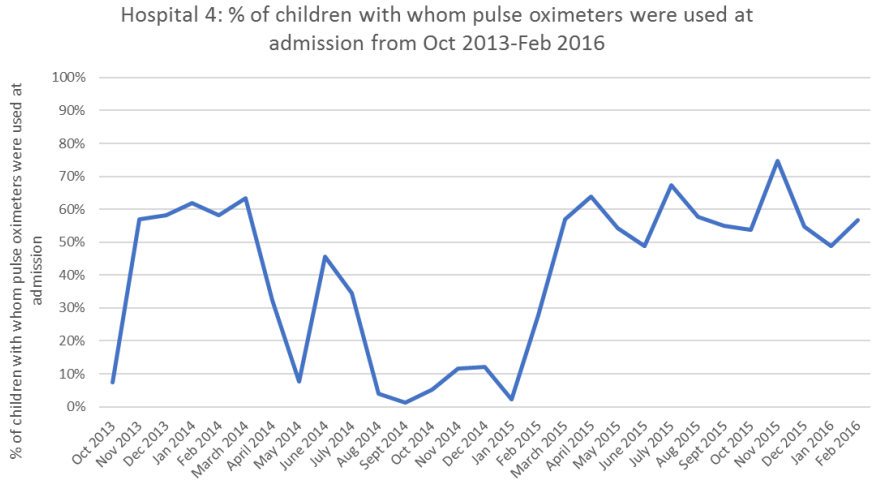
Note that in low-income countries children often have multiple ARI episodes per year. The estimates for the baseline (when pulse oximeters are not used) were the following: low estimate for referral rates from primary care facilities: 100 (1%); high estimate: 500 (5%); low estimate for admission from ED: 500 (5%); high estimate: 1500 (15%). Referral and admission rates for when pulse oximeters are used were estimated by assuming an increase or decrease in primary care referrals / emergency department admissions of 5-50% over or below the baseline referral / admission rates. Hypoxemia prevalence in children aged 7 days-36 months presenting to an emergency department with ARI has been shown to be as high as 59%[Onyango et.al.1993] (when hypoxemia defined as SaO2<91%) so these high estimates for referral / admission rates are reasonable. Referral / admission rates would be higher in a population if: the true hypoxemia prevalence in the population is higher (e.g. due to high altitude, seasonal effects on bronchiolitis, predisposing environmental factors for asthma); a larger proportion of hypoxemic children are being missed by clinical evaluation; or higher thresholds are used to define hypoxemia. The converse of these conditions would lead to lower referral / admission rates, as would a reduction in the number of false-positives as a result of improved accuracy of hypoxemia diagnosis over clinical signs.

Appendix 3.1: figures of pulse oximeter use over time for each of the 14 CIN hospitals



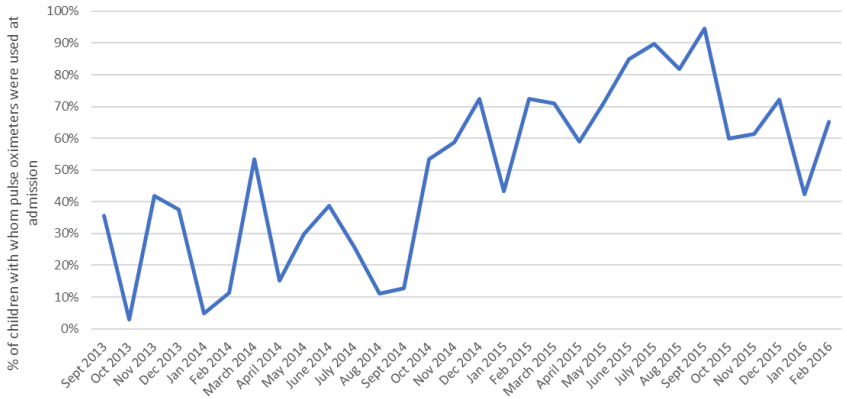




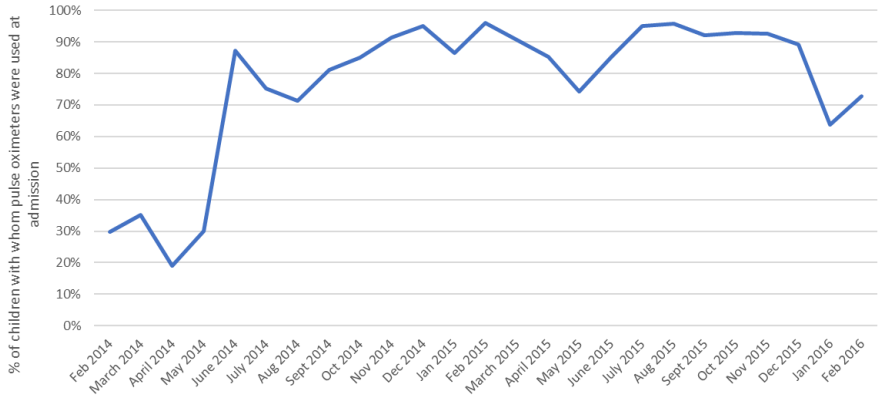


Hospital 5: % of children with whom pulse oximeters were used at admission from Sept 2013-Feb 2016

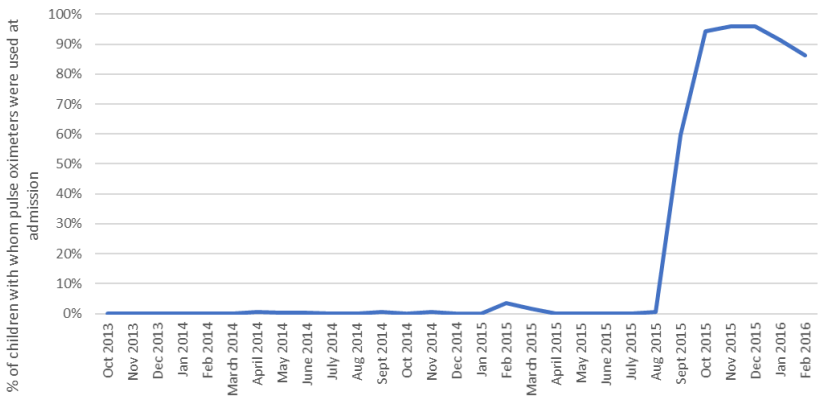
Hospital 6: % of children with whom pulse oximeters were used at admission from Sept 2013-Feb 2016

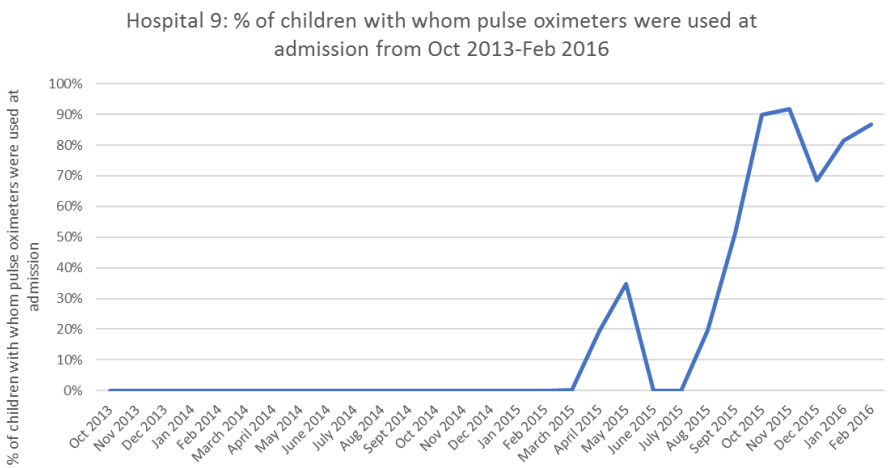


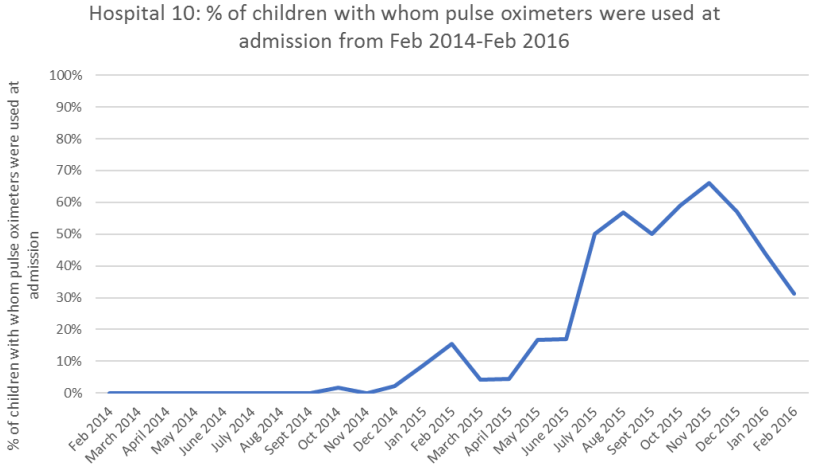
Hospital 7: % of children with whom pulse oximeters were used at admission from Feb 2014-Feb 2016

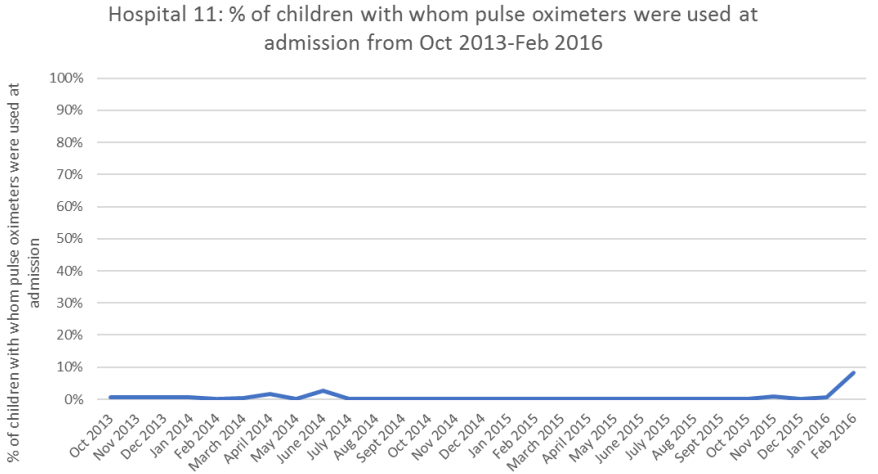


Hospital 8: % of children with whom pulse oximeters were used at admission from Oct 2013-Feb 2016




Hospital 9: % of children with whom pulse oximeters were used at admission from Oct 2013-Feb 2016
% of children with whom pulse oximeters were used at admission
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Oct 2013
Nov 2013
Dec 2013
Jan 2014
Feb 2014
March 2014
April 2014
May 2014
June 2014
July 2014
Aug 2014
Sept 2014
Oct 2014
Nov 2014
Dec 2014
Jan 2015
Feb 2015
March 2015
April 2015
May 2015
June 2015
July 2015
Aug 2015
Sept 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016


Hospital 10: % of children with whom pulse oximeters were used at admission from Feb 2014-Feb 2016
% of children with whom pulse oximeters were used at admission
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Feb 2014
March 2014
April 2014
May 2014
June 2014
July 2014
Aug 2014
Sept 2014
Oct 2014
Nov 2014
Dec 2014
Jan 2015
Feb 2015
March 2015
April 2015
May 2015
June 2015
July 2015
Aug 2015
Sept 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016


Hospital 11: % of children with whom pulse oximeters were used at admission from Oct 2013-Feb 2016
% of children with whom pulse oximeters were used at admission
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Oct 2013
Nov 2013
Dec 2013
Jan 2014
Feb 2014
March 2014
April 2014
May 2014
June 2014
July 2014
Aug 2014
Sept 2014
Oct 2014
Nov 2014
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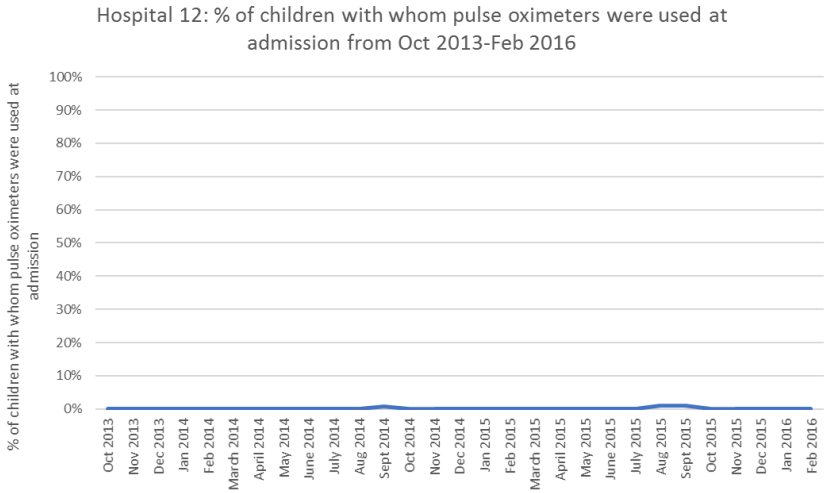
Nov 2015
Dec 2015
Jan 2016
Feb 2016


Hospital 12: % of children with whom pulse oximeters were used at admission from Oct 2013-Feb 2016
% of children with whom pulse oximeters were used at admission
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Oct 2013
Nov 2013
Dec 2013
Jan 2014
Feb 2014
March 2014
April 2014
May 2014
June 2014
July 2014
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Jan 2015
Feb 2015
March 2015
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Oct 2015
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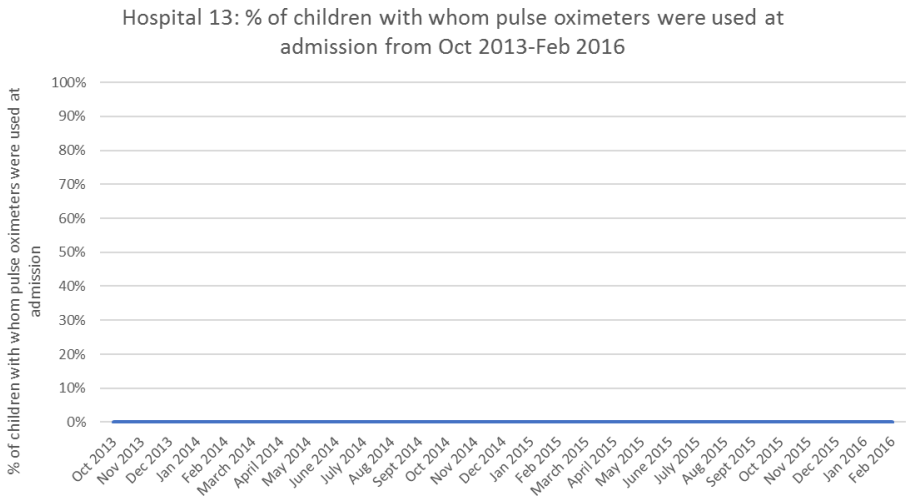
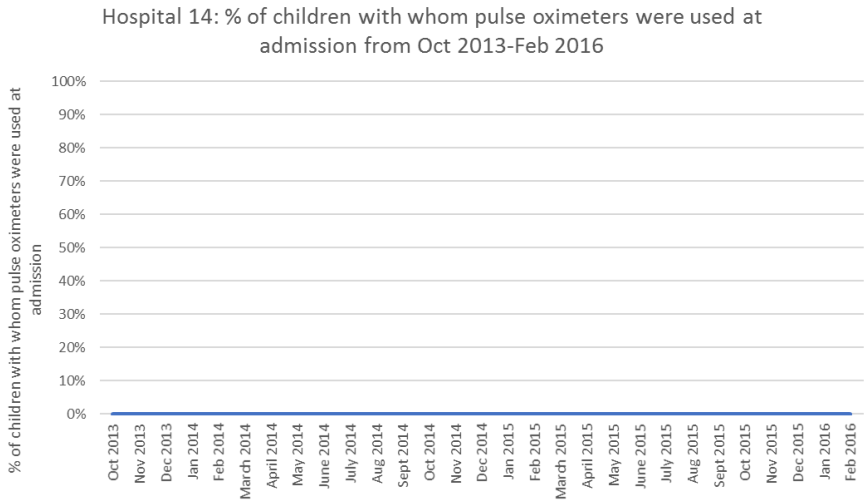
Dec 2015
Jan 2016
Feb 2016


Hospital 13: % of children with whom pulse oximeters were used at admission from Oct 2013-Feb 2016
% of children with whom pulse oximeters were used at admission
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Oct 2013
Nov 2013
Dec 2013
Jan 2014
Feb 2014
March 2014
April 2014
May 2014
June 2014
July 2014
Aug 2014
Sept 2014
Oct 2014
Nov 2014
Dec 2014
Jan 2015
Feb 2015
March 2015
April 2015
May 2015
June 2015
July 2015
Aug 2015
Sept 2015
Oct 2015
Nov 2015
Dec 2015
Jan 2016
Feb 2016


Hospital 14: % of children with whom pulse oximeters were used at admission from Oct 2013-Feb 2016
% of children with whom pulse oximeters were used at admission
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Oct 2013
Nov 2013
Dec 2013
Jan 2014
Feb 2014
March 2014
April 2014
May 2014
June 2014
July 2014
Aug 2014
Sept 2014
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Dec 2014
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Nov 2015
Dec 2015
Jan 2016
Feb 2016

Appendix 3.2: Factors across the levels of the health system hierarchy that might impact uptake of a technology (factors specific to pulse oximetry are shown in Figure 7.2)

National/MoH

International and national policy (e.g. guidelines), and their dissemination; centralised finance/purchasing; training (e.g. medical schools); priority setting

County

Finance/purchasing; training; priority setting

Hospital

Finance/purchasing; training; priority setting; process for procuring and maintaining equipment

Departmental

Staff culture/professional norms; training from other departmental staff; priority setting; senior staff leadership and the expectations and rules they establish

Individual

Past experiences; knowledge; beliefs/attitudes; priority setting

Appendix 3.3: List of 74 CIN variables for which I obtained data

Variable	Description
Date admitted	Day/month/year of admission
Hospital	Hospital where child was admitted (n=7)
Age in years	Age in years (0-15)
Age in months	Age in months for children under 1 year
Age less than one month	Whether child is under one month old (yes, no)
Weight	Weight (kg)
Sex	Female, male
Pediatric Admission Record use	No PAR, PAR present not used, PAR used
Length of illness before admission	Number of days of illness before admission (1-21)
Fever	Whether had fever (yes, no)
Cough	Whether had cough (yes, no)
Difficulty breathing	Whether had difficulty breathing (yes, no)
Diarrhoea	Whether had diarrhoea (yes, no)
Vomits	Whether were vomiting (yes, no)
Vomit everything	Whether was vomiting everything (yes, no)
Difficulty feeding	Whether had difficulty feeding (yes, no)
Convulsions	Whether had convulsions (yes, no)
Respiratory rate	Respiratory rate (per minute)
Pulse oximeter use	Whether a pulse oximeter reading was taken (yes, no)
Pulse oximeter value	The pulse oximeter value (0-100%)
Oedema	Whether had oedema (face, foot, knee, none)
Stridor	Whether had stridor (yes, no)
Central cyanosis	Whether had central cyanosis (yes, no)
Indrawing	Whether had chest indrawing (yes, no)
Grunting	Whether was grunting (yes, no)
Wheeze	Whether was wheezing (yes, no)
Crackles	Whether had crackles (yes, no)
Capillary refill	Capillary refill time (in seconds)
Pallor	Whether had pallor (+ (mild or moderate), +++ (severe pallor), none)
Lack of alertness	Alertness level (alert, verbal response, pain response, unresponsive)
Difficulty drinking	Whether had difficulty drinking (yes, no)
Stiff neck	Whether had stiff neck (no/soft, yes)
Bulging fontanelle	Whether had bulging fontanelle (no/flat, yes)
Malaria test result (if malaria test taken)	Malaria test result (positive/negative)
Diagnosis 1: malaria	Type of malaria, if have malaria diagnosis as primary diagnosis
Diagnosis 1: malaria severe	Type of severe malaria, if have severe malaria as primary diagnosis
Diagnosis 1: malaria non-severe	Type of non-severe malaria, if have non-severe malaria as primary diagnosis
Diagnosis 1: malaria no class	Type of malaria not classified by severity, if have malaria not classified by severity as primary diagnosis
Diagnosis 1: pneumonia	Type of pneumonia, if have pneumonia as primary diagnosis

Diagnosis 1: diarrhoea	Type of diarrhoea, if have diarrhoea as primary diagnosis
Diagnosis 1: dehydration	Type of dehydration, if have dehydration as primary diagnosis
Diagnosis 1: malnutrition	Type of malnutrition, if have malnutrition as primary diagnosis
Diagnosis 1: anaemia	Type of anaemia, if have anaemia as primary diagnosis
Diagnosis 1: meningitis	Whether have meningitis as primary diagnosis (yes, no)
Diagnosis 1: asthma	Type of asthma, if have asthma as primary diagnosis
Diagnosis 1: TB	Whether have TB as primary diagnosis (yes, no)
Diagnosis 1: other 1	Primary diagnosis (from a drop down list based on previous free written answers)
Diagnosis 1: other 2	A second primary diagnosis (from a drop down list based on previous free written answers))
Diagnosis 1: other 3	A third primary diagnosis (from a drop down list based on previous free written answers))
Diagnosis 1: other 4	A fourth primary diagnosis (from a drop down list based on previous free written answers))
Diagnosis 1: other 3 written in free text	A fifth primary diagnosis (free written)
Diagnosis 2: malaria	Type of malaria, if have malaria diagnosis as secondary diagnosis
Diagnosis 2: malaria severe	Type of severe malaria, if have severe malaria as secondary diagnosis
Diagnosis 2: malaria non-severe	Type of non-severe malaria, if have non-severe malaria as secondary diagnosis
Diagnosis 2: malaria no class	Type of malaria not classified by severity, if have malaria not classified by severity as secondary diagnosis
Diagnosis 2: pneumonia	Type of pneumonia, if have pneumonia as secondary diagnosis
Diagnosis 2: diarrhoea	Type of diarrhoea, if have diarrhoea as secondary diagnosis
Diagnosis 2: dehydration	Type of dehydration, if have dehydration as secondary diagnosis
Diagnosis 2: malnutrition	Type of malnutrition, if have malnutrition as secondary diagnosis
Diagnosis 2: anaemia	Type of anaemia, if have anaemia as secondary diagnosis
Diagnosis 2: meningitis	Whether have meningitis as secondary diagnosis (yes, no)
Diagnosis 2: asthma	Type of asthma, if have asthma as secondary diagnosis
Diagnosis 2: TB	Whether have TB as secondary diagnosis (yes, no)
Diagnosis 2: other 1	Secondary diagnosis (from a drop down list based on previous free written answers)
Diagnosis 2: other 2	A second secondary diagnosis (from a drop down list based on previous free written answers))
Diagnosis 2: other 3	A third secondary diagnosis (from a drop down list based on previous free written answers))
Diagnosis 2: other 4	A fourth secondary diagnosis (from a drop down list based on previous free written answers))
Diagnosis 2: other 3 written in free text	A fifth secondary diagnosis (free written)
Quinine	Whether quinine given (yes, no)
Artesunate	Whether artesunate given (yes, no)
Artemether	Whether artemether given (yes, no)
Coartem (Artemether/ Lumefantrine)	Whether coartem given (yes, no)
Oxygen ordered	Whether oxygen given (yes, no)
Outcome	Outcome (alive, died, referred, absconded, discharged against advice)

Appendix 3.4: Data Management Plan

Data Management Plan

Researcher:

Abigail Enoch

Project title:

Pulse oximeter use in Kenyan hospitals

Project duration:

04/2015-09/2017

Project context:

The research project aims to determine a) when pulse oximeters are used for children aged 1 month to 12 years in Kenyan hospitals, in terms of in which patients and hospitals, and how this has changed over time; and b) how health outcomes are affected by the use of pulse oximeters.

This research is being carried out as part of a DPhil project at Oxford's Nuffield Department of Population Health.

1. What data will be produced?

The data that will be used for this research will be obtained from the Clinical Information Network (CIN). This CIN was developed to collect data on children entering 14 hospitals in Kenya, including demographic information, their symptoms, diagnosis, their physicians' decisions on treatment, and their outcomes. The CIN was developed through a collaboration between the Kenya Medical Research Institute (KEMRI) Wellcome Trust Research Programme's (KWTRP) Health Services Unit (HSU), the Kenyan Ministry of Health, and the Kenya Paediatric Association.[Gachau et.al.2017; Tuti et.al.2016a]

KWTRP was established by formal Memorandum of Understanding between Oxford and the Wellcome Trust.[English, personal communication] KEMRI was created as part of the 1979 Science and Technology (Amendment) Act, to provide a national medical research agency with the responsibility of undertaking biomedical research.[KEMRI]

The KEMRI Data Governance Committee has accepted our data transfer agreement application and has therefore agreed to transfer the data from Kenya to us in the UK.

First descriptive analyses of the data will be conducted. Then we will statistically analyse, using R software, whether pulse oximeter use varies by child characteristics, hospital, and/or time, and whether health outcomes vary depending on pulse oximeter use.

Statistical analyses will be carried out in R and will involve regressions and interrupted time series. When not being analysed the data will be stored in CSV files – one for the dataset containing the date of discharge/death variable data, and one for the dataset that does not contain this information.

2. How will the data be documented and described?

An excel file of the metadata is available that lists all of the variables for which data have been collected. The descriptive analyses section of the analyses will also serve to document and describe the data as a whole.

3. How will the data be stored and backed up during the lifetime of the project?

All data apart from the sensitive variable of date of discharge/death (which could be used in conjunction with another variable to determine date of death) will be stored on Abigail Enoch's laptop which will be encrypted. These data and any analyses and related documents will be backed up daily by Abigail Enoch to the Oxford TSM backup service and/or to encrypted USB drives.

A separate folder containing the date of discharge/death data will be stored on the Oxford High Compliance System and all analyses involving this variable will be undertaken by Abigail Enoch solely within the High Compliance System. This data will be automatically backed up to the Oxford server.

4. Legal and ethical issues

The CIN data that will be used are part of Kenyan government research. Not only are Oxford researchers involved with this, but also key officers in the Ministry of Health are co-investigators for the proposal of the overall database. This database is just one of many projects that have involved collaboration between Oxford researchers and the Kenyan government, as this KWTRP partnership has existed for roughly 25 years. This partnership's goal is to share and develop Kenyan technical expertise.[English, personal communication]

The data is anonymized.

The only potentially identifiable information in the original dataset is that date of birth and date of death could theoretically be calculated. The date of birth could be calculated from the combination of data from the 'date of admission' variable and the 'age in days' variable for children less than 1 month old. For this reason the data for the age in days of the children less than 1 month old will not be used – only the variable of whether the child is greater or less than 1 month old will be used for these children. The date of death could theoretically be calculated from the combination of data from the 'outcome – alive/dead' variable and the 'date of discharge/death' variable. For this reason data for the date of discharge/death variable will be kept on the secure Oxford High Compliance System and all analyses involving this variable will be conducted on this system.

KEMRI has guidelines for research that is conducted by its researchers, and it has a disciplinary committee which monitors and confirms whether research is conforming to its requirements. KEMRI has a research and ethics committee which has final ethical approval power for research conducted by its researchers, such as the collection of data through this CIN database.[KEMRI] KEMRI has provided ethical approval for these data's collection (SSC 2465). The ethical committee provided an exemption from having to obtain consent for the collection of these data as they come from medical records completed only after the child has been discharged, and because the data are anonymized, and therefore they decided the data provided minimal/less than minimal risk. Professor Mike English, who is the DPhil supervisor of Abigail Enoch, is the Principal Investigator on the main project for which the CIN data has been collected.[English, personal communication]

When the annual request for renewal of the research committee's approval of this data was recently being undertaken, Abigail Enoch was added as a co-investigator with a specific role to analyse some of the data.[English, personal communication]

The KEMRI Data Governance Committee has approved our data sharing agreement application, thereby enabling the data to be transferred to us.

5. What are the plans for long-term archiving and data sharing after submission of the thesis?

The data will be kept in the Oxford archive for three years after the end of the DPhil research project ends. After this period the data will be destroyed.

Data used for the thesis will be subject to the data sharing guidelines of KEMRI.

Information about the study and the data sharing guidelines will be readily discoverable by other researchers: a description of the study and metadata will be available on the MRC Research Data Gateway, along with information on KEMRI's data sharing guidelines.

Due to the data sharing policy of KEMRI we will not be able to make the dataset that we develop available to others. This is particularly the case given that the data we will be obtaining based on our ethical approval is in effect a copy of medical records data that is officially primarily owned by the Kenyan Ministry of Health and the hospitals from which the records come. The sensitivity of this situation is further emphasized by the fact that we are non-Kenyan investigators from a non-Kenyan institution using Kenyan data.

This research is partly funded by the Medical Research Council (MRC) which follows the Research Council UK's (RCUK) policy on open access. Thus in accordance with this, any publications resulting from this research will be through open-access journals.

Any publications and other reports will acknowledge the Kenyan Ministry of Health, the KEMRI Wellcome Trust Research Programme, the Kenyan Paediatric Association, and the Medical Research Council.

Signed: Abigail Enoch

Date Created: 16th April 2015

Appendix 3.5: Ethical approval letters from KEMRI and CUREC for use of the CIN data

KEMRI | Wellcome Trust

Letter of Permission for Use of Data

MEMORANDUM

Date: 13th April 2015

Requestor: Abigail Enoch
University of Oxford

Provider: Prof Mike English
Study Principal Investigator
KEMRI CGMR-C and University of Oxford

Approved By: KEMRI CGMR-C Data Governance Committee

RE: DATA SHARING REQUEST

This letter is to inform you that your data request was discussed and approved at the KEMRI CGMR-C Data Governance Committee meeting held on 10th April 2015.

Permission is granted for provider to share the data requested for analyses as specified in the request form. The provider is the Principal Investigator of the data collected under "SSC 2465: Understanding morbidity and mortality and examining strategies to improve uptake of recommended practices for care of seriously ill children and newborns in Kenyan hospitals."

The requestor agrees to abide by the conditions and limitations of data sharing as set out in the request form.

Signed:

Philip Bejon
Programme Director
KEMRI CGMR-C Data Governance Committee Chair

Enc.

Data Sharing Request Form

KEMRI-Wellcome Trust Research Programme
CGMRC, PO Box 230-80108, Kilifi, Kenya
Tel : +254 730 163 000
Fax : +254 41 7522390
Website : www.kemri-wellcome.org
Email : info@kemri-wellcome.org

MS IDREC

Research Services, University of Oxford

University Offices, Wellington Square, Oxford, OX1 2JD

Tel: +44(0)1865 616577

Email: ethics@medsci.ox.ac.uk

Miss Abigail Enoch
St Edmund Hall
Queen's Lane
Oxford

5th June 2015

Dear Abigail

CUREC application: Pulse Oximeter use in Kenyan hospitals

I am pleased to confirm that this application has been reviewed by the Officer of the relevant Oxford University Ethics Committee, with reference to formally approved process and has determined that it does not raise any issues of research ethics with human participants.

Yours sincerely

Gill Halstead

Gill Halstead

Research Ethics Co-ordinator, Medical Sciences
Research Services
University of Oxford
University Offices, Wellington Square. OX1 2JD
T: +44 01865 616575 **E:** ethics@medsci.ox.ac.uk

Please note I work Monday, Wednesday and Thursday

www.admin.ox.ac.uk/researchsupport

Appendix 3.6: what was done to/with each variable during the cleaning and organising process

Variable	**Type: old used to create new; adapted; new**	**Details of what was done with / to the variable**	**Why change was made / new variable created**
Date admitted (day / month / year)	Old	Was used to create *Admission month*, *Year of admission*, *Weekend admission*	We did not need information as specific as the actual day of admission; using such specific information when not necessary raises ethical issues
Admission month	New	Created from *Date admitted* using coding in R	It was important to have the month of admission because diagnoses could vary by month based on seasonality (and therefore pulse oximeter and oxygen use might vary by month), recording could vary by month because of holidays taken by HCWs and data clerks, practices could vary by month depending on HCW rotations.
Year of admission	New (just created to be able to create *Admission time period*)	Created from *Date admitted* using coding in R	Created to be able to then create *Admission time period*
Weekend admission	New	Created from *Date admitted* using coding in R	It was thought that care quality may be different on weekends because of fewer staff being present then

Admission time period	New	Created by sorting children by *Admission month* and *Year of admission*, and grouping into six-month periods	It was thought that pulse oximeter use and other practices could have changed over time because of general improvements over time, events such as guideline introductions, increased familiarity with the CIN and its recording system and recommendations, and the build-up of CIN feedback
Hospital	No changes	No changes made	n/a
Age in years	Adapted	Rounded the years with decimals down to nearest year	-There was only a handful of times that years were listed with decimals so we rounded the years to standardize; we rounded down because children who are 3 years and 11 months are considered 3 years old. -This variable was then to be used to determine which children were under one month or over 12 years and so should be removed; and to be used as a control variable in the regressions
Age in months	Old	-Rounded the months with decimals down to the nearest month -If >12 months, changed value to 'NA' unless *Age in years* could correspond, in which case made the appropriate changes -Changed values of '12' to '0' if *Age in years* had value of 1 -Changed values of '12' to '11' if *Age in years* had value of '0'	All of these changes were made as part of the process to work out which children were under one month and so should be removed from the dataset

		-Changed values to 'NA' if *Age in years* had value >1	
Age in months when less than 1 year	New (just created to know which children were under one month and so should be removed)	-To create the variable, first entered in all of the *Age in months* values -Replaced values with 'NA' if *Age in years* was >0 or *Age in years* had value of 'NA' -See Appendix 4.6	All of these changes were made as part of the process to work out which children were under one month and so should be removed from the dataset[i]
Age less than one month	Old	No changes made	This variable was used as part of the process to work out which children were under one month and so should be removed from the dataset
Weight	Old	No changes made	Used with *Age in years* to create new *Weight-for-age* variable
Weight-for-age	New	Created from *Weight* and *Age in years*: a) Weight / Age; b) Compared this with the z scores of the reference data from the WHO's Multicentre Growth Reference Study (for children aged 1 month to 10 years) and the Canadian Paediatric Endocrine Group (for 11-19 year olds), using the Canadian Paediatric Endocrine Group's statistical program[refx5]	To have a standardized weight measure that takes age into account; an indicator of malnutrition
Sex	Adapted	Dichotomized: changed values of 'Female' to '1' and 'Male' to '0'	To make a binary variable

Pediatric Admission Record use	No changes made	No changes made	n/a
Length of illness before admission	Adapted	-Rounded up any values with decimals and changed the few values of '0' to '1' -Created histogram of values and thereby worked out that 4 days was a logical cutoff as number of children tapered off substantially above this value -Replaced all values >4 with '4+'	Adapted to create a more manageable variable
Fever	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Cough	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Difficulty breathing	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Diarrhoea	Old	Used to create *Diagnosis diarrhoea*	To help create *Diagnosis diarrhoea*
Vomits	Old	Used to adapt *Vomit everything*	To make *Vomit everything* more accurate
Vomit everything	Adapted	-When *Vomits* had value of 'no' changed all NA values of *Vomit everything* to '0' -Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	-To make more accurate -To make a binary variable
Difficulty feeding	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable

Convulsions	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Respiratory rate	Adapted	Children were given a '1' if they had a very high respiratory rate (defined as >70 for children 1-11 months, >60 for children aged 1-4 years, and >45 for children aged 5-12 years) and a '0' if they had a low or normal respiratory rate. This threshold was because roughly 15% of children in the dataset in each of these age brackets had respiratory rates above these levels; these thresholds are supported by the literature.	To make a binary variable
Pulse oximeter use	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Pulse oximeter value	Adapted	-Dichotomized: changed values <90% to '1' and values ≥90% to '0' -In the multiple imputation and Research Question 3 regression model, children with a *Pulse oximeter use* value of 0 or NA were not included	-It is very rare to obtain a reading below 70% so it was presumed that these values were errors -To make a binary variable (the WHO and Kenyan Basic Paediatric Protocols recommend giving oxygen when value is <90%
Oedema	Adapted	Dichotomized: changed values of 'Face', 'Foot' or 'Knee' to '1' and values of 'None' to '0'	To make a binary variable
Stridor	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Central cyanosis	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable

Indrawing	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Grunting	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Wheeze	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Crackles	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Capillary refill	Adapted	Dichotomized: changed values of >3 seconds to '1' and values ≤3 seconds to '0'; the Kenyan Basic Paediatric Protocols classifies a capillary refill of >3 seconds as an emergency sign to look for when triaging children	To make a binary variable
Pallor	Adapted	Dichotomized: changed values of '+' (mild or moderate) or '+++' (severe pallor) to '1' and values of 'None' to '0'	To make a binary variable
Lack of alertness	Adapted	Dichotomized: changed values of 'Verbal response', 'Pain response' and 'Unresponsive' to '1' and values of 'Alert' to '0'	To make a binary variable
Difficulty drinking	Adapted	Dichotomized: changed values of 'No' (for can drink) to '1' and values of 'Yes' (for can drink) to '0'	To make a binary variable
Stiff neck	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable

Bulging fontanelle	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To make a binary variable
Malaria test result (if malaria test taken)	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions
Diagnosis 1: malaria	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions
Diagnosis 1: malaria severe	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions
Diagnosis 1: malaria non-severe	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions
Diagnosis 1: malaria no class	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions
Diagnosis 1: pneumonia	Old	Used to make new *Diagnosis pneumonia*	To make new *Diagnosis pneumonia* which can be controlled for in the regressions and can be used for doing analyses specifically with children with pneumonia
Diagnosis 1: diarrhoea	Old	Used to make new *Diagnosis diarrhoea*	To make new *Diagnosis diarrhoea* which can be controlled for in the regressions
Diagnosis 1: dehydration	Old	Used to make new *Diagnosis dehydration*	To make new *Diagnosis dehydration* which can be controlled for in the regressions
Diagnosis 1: malnutrition	Old	Used to make new *Diagnosis malnutrition*	To make new *Diagnosis malnutrition* which can be controlled for in the regressions

Diagnosis 1: anaemia	Old	Used to make new *Diagnosis anaemia*	To make new *Diagnosis anaemia* which can be controlled for in the regressions
Diagnosis 1: meningitis	Old	Used to make new *Diagnosis meningitis*	To make new *Diagnosis meningitis* which can be controlled for in the regressions
Diagnosis 1: asthma	Old	Used to make new *Diagnosis asthma*	To make new *Diagnosis asthma* which can be controlled for in the regressions
Diagnosis 1: TB	Old	Used to make new *Diagnosis TB*	To make new *Diagnosis TB* which can be controlled for in the regressions
Diagnosis 1: other 1	Old	Used to make new diagnoses variables	To make new diagnoses variables which can be controlled for in the regressions
Diagnosis 1: other 2	Old	As above	As above
Diagnosis 1: other 3	Old	As above	As above
Diagnosis 1: other 4	Old	As above	As above
Diagnosis 1: other 3 written in free text	Old	As above	As above
Diagnosis 2: malaria	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions
Diagnosis 2: malaria severe	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions
Diagnosis 2: malaria non-severe	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions

Diagnosis 2: malaria no class	Old	Used to make new *Diagnosis malaria*	To make new *Diagnosis malaria* which can be controlled for in the regressions
Diagnosis 2: pneumonia	Old	Used to make new *Diagnosis pneumonia*	To make new *Diagnosis pneumonia* which can be controlled for in the regressions and can be used for doing analyses specifically with children with pneumonia
Diagnosis 2: diarrhoea	Old	Used to make new *Diagnosis diarrhoea*	To make new *Diagnosis diarrhoea* which can be controlled for in the regressions
Diagnosis 2: dehydration	Old	Used to make new *Diagnosis dehydration*	To make new *Diagnosis dehydration* which can be controlled for in the regressions
Diagnosis 2: malnutrition	Old	Used to make new *Diagnosis malnutrition*	To make new *Diagnosis malnutrition* which can be controlled for in the regressions
Diagnosis 2: anaemia	Old	Used to make new *Diagnosis anaemia*	To make new *Diagnosis anaemia* which can be controlled for in the regressions
Diagnosis 2: meningitis	Old	Used to make new *Diagnosis meningitis*	To make new *Diagnosis meningitis* which can be controlled for in the regressions
Diagnosis 2: asthma	Old	Used to make new *Diagnosis asthma*	To make new *Diagnosis asthma* which can be controlled for in the regressions
Diagnosis 2: TB	Old	Used to make new *Diagnosis TB*	To make new *Diagnosis TB* which can be controlled for in the regressions
Diagnosis 2: other 1	Old	Used to make new diagnoses variables	As above
Diagnosis 2: other 2	Old	As above	As above
Diagnosis 2: other 4	Old	As above	As above

Diagnosis 2: other 3	Old	As above	As above
Diagnosis 2: other 3 written in free text	Old	As above	As above
Diagnosis pneumonia	New	-Created from the 36 old diagnoses variables: thousands of diagnosis variants were categorised into new diagnosis categories and then code was created in R to create the 11 new diagnosis variables[ii], including *Diagnosis pneumonia* -A child is classified as '1' if the HCW recorded that they had any type of pneumonia, even if they were also classified as having another/other diagnosis(es); a child is classified as '0' if the HCW did not record that they had pneumonia. -Based on advice from key informants familiar with the Kenyan hospital setting, it was assumed that if a diagnosis was not listed, then the HCW who recorded this information did not assess the child as having the diagnosis, i.e. this variable had no missing data.	To be able to control for it in the regressions and to use for doing analyses specifically with children with pneumonia
Diagnosis malaria	New	Created from the old diagnoses variables – see *Diagnosis pneumonia* for more information	To be able to control for it in the regressions
Diagnosis TB	New	As above	As above
Diagnosis diarrhoea	New	As above	As above

Diagnosis dehydration	New	As above	As above
Diagnosis malnutrition	New	As above	As above
Diagnosis anaemia	New	As above	As above
Diagnosis meningitis	New	As above	As above
Diagnosis asthma	New	As above	As above
Diagnosis bronchiolitis	New	As above	As above
Diagnosis sepsis	New	As above	As above
Quinine	Old	Used to create new *Antimalarials*	To be able to control for *Antimalarials* in the regressions
Artesunate	Old	Used to create new *Antimalarials*	To be able to control for *Antimalarials* in the regressions
Artemether	Old	Used to create new *Antimalarials*	To be able to control for *Antimalarials* in the regressions
Coartem (Artemether/ Lumefantrine)	Old	Used to create new *Antimalarials*	To be able to control for *Antimalarials* in the regressions
Antimalarials	New	-Created from *Quinine*, *Artesunate*, *Artemether* and *Coartem* -Children were given an 'inject' in the new *Antimalarials* variable if they had a 'Yes' for the original *Quinine* or *Artesunate* or *Artemether* variable; children were given an 'oral' for the new	To be able to control for *Antimalarials* in the regressions

		Antimalarials variable if they had a 'No' for the original *Quinine*, *Artesunate* and *Artemether* variables, but had a 'Yes' for the original *Coartem* (Artemether/Lumefantrine) variable; children were given a 'neither' if they had a 'No' for all four of the aforementioned original antimalarial variables. -Based on advice from key informants familiar with the Kenyan hospital setting, it was assumed that antimalarial 'NA' values indicated the treatment was not given, because as part of the prescription process, HCWs record all treatments provided; thus this variable had no missing data.	
Oxygen ordered	Adapted	Dichotomized: changed values of 'Yes' to '1' and values of 'No' to '0'	To create binary variable
Outcome	Adapted	Changed 'absconded' and 'discharged against advice' to 'Other'	To simplify the variable

[i] *Age in years*, *Age in months* and *Age less than one month* were not always consistent and so it was not always evident which children were aged less than one month: e.g. *Age in months* was meant to give values only for children under one years old, but sometimes gave values for older children (values that were not the years equivalent in months); similarly, *Age less than one month* sometimes had a value of 'Yes' even when *Age in months* or *Age in years* had values greater than one. I therefore created an *Age in months no years* variable that included the *Age in months* values when *Age in years* was '0' (otherwise the *Age in months no years* value was 'NA'), and then using Appendix 4.6's table, used the *Age in years*, *Age in months no years* and *Age less than one month* values to decide which children could be assumed to be less than one month old.

[ii] To create the diagnoses variables, I first had to manually go through each of the thousands of listed diagnoses (the same diagnosis may have been written in multiple ways because of different types of the diagnosis, spelling differences/inaccuracies, different specifications about the diagnosis in terms of severity, location etc., combinations with other diagnoses, other notes written by the HCW, etc.) and categorize each into one of the 11 diagnoses of interest or a 12th category of other diagnoses. Once I had a list of every diagnosis from the old 36 diagnoses variables that I wanted to categorize into the 11 new diagnoses variables (there were, for instance, 196 separate listings for the new *Diagnosis sepsis* variable), I created a code in R to create these new variables and enter in values of '1' or '0' depending on whether the child had any of the diagnoses categorized into the 11 categories. The original diagnoses variants, within the original diagnoses variables, that were categorized into each new diagnosis variable are listed in Appendix 4.7.

Appendix 3.7: how to decide whether a child is less than one month old and so should be removed from the dataset

As mentioned in Section 3.8.1, sometimes the *Age in years*, *Age less than one month*, and *Age in months no years* variables contradicted each other, making it difficult to know whether a child was less than one month old and so should be excluded from the dataset, based on the exclusion criteria discussed in Section 3.5.2.

I therefore decided on the following logic to decide whether to keep a child in the dataset or remove them, based on these three variables. This is shown in the below table. Highlighted rows are those where variables contradicted each other. Note: *Age in months no years* is a variable that indicates the age in months of children who are less than one year old, with a value of NA if one year or older; as this variable was created partly based on the *Age in years* variable (see Appendix 3.6), if the *Age in years* variable has a value of NA, the *Age in months no years* variable must also have a value of NA.

The logic used was to essentially trust the *Age in years* variable completely; and to trust *Age in months no years* over *Age less than one month*, a decision made because it seems more likely that someone would mistakenly enter yes vs. no or vice versa (for *Age less than one month*), than to mistakenly enter a number (for *Age in months no years*); the exception is when *Age less than one month* had a value of 'Yes' and *Age in months no years* had a value of '1'; in this situation the child was removed as it was assumed that the age of the child had been rounded up to 1 month for *Age in months no years*.

Age in years	***Age less than one month***	***Age in months no years***	**Remove child from dataset or keep in**
0	Yes	0	Remove
≥1	anything	anything	Keep
0	No	0	Remove
0	Yes	1	Remove
0	Yes	>1	Keep
0	No	≥1	Keep
0	Yes	NA	Remove
NA	Yes	0	NA (values combination not possible)
0	NA	0	Remove
NA	Yes	NA	Keep
NA	NA	0	NA (values combination not possible)
0	NA	NA	Keep
NA	NA	NA	Keep

Appendix 3.8: diagnoses categorized into new diagnosis categories

Diagnosis pneumonia:

Diagnosis 1: pneumonia:

Pneumonia(No classification)[ICD10: J18.9]

Pneumonia(Non Severe)[ICD10: J18.9A]

Pneumonia(severe)[ICD10: J18.9B]

Pneumonia(Very severe)[ICD10: J18.9C]

Diagnosis 2: pneumonia:

Pneumonia(No classification)[ICD10: J18.9]

Pneumonia(Non Severe)[ICD10: J18.9A]

Pneumonia(severe)[ICD10: J18.9B]

Pneumonia(Very severe)[ICD10: J18.9C]

Diagnosis 1: other 1:

Broncho pneumonia

PCP

Diagnosis 1: other 3:

aspiation pneumonia

Aspiration Pneumonia

aspiration pneumonia

aspration pneumonia

B20.6 HIV disease resulting in Pneumocystis carinii pneumonia

B20.6,HIV disease resulting in Pneumocystis carinii pneumonia

B20.6,PCP /PJP

B20.6,Pneumocytis pneumonia

B59,Pneumocystosis

B59,Pneumonia carinis Pneumonia

Bronchopneumonia

J17.3 Pneumonia in parasitic diseases

J18.0,Broncho pneumonia

J18.0,Bronchopneumonia, unspecified

J18.9,Pneumonia, unspecified

J69.0 Aspiration pneumonia

J69.0, ASPIRATION PNEUMONIA

J69.0, Aspiration Pneumonia

J69.0Aspiration pneumonia

O74.0,Aspiration pneumonitis due to anaesthesia during labour and delivery

P36.8,NEONATAL: Pneumonia

Diagnosis 1: other 4:

aspiration pneumonia

aspiraton pneumonia

B20.6,HIV disease resulting in Pneumocystis carinii pneumonia

B20.6,PCP /PJP

B20.6,Pneumocytis pneumonia

chemical pneumonia

inhalatonal pneumonia

J18.0 Bronchopneumonia, unspecified

J18.0,Bronchopneumonia, unspecified

J69.0 Aspiration pneumonia

Diagnosis 1: other 3 written in free text:

aspiartion pneumonia secondary to paraffin ingestion

aspiartion pneumonia, paraffin poisoning

Aspiration pneumonia

aspiration pneumonia

ASPIRATION PNEUMONIA

Aspiration Pneumonia

Aspiration Pneumonia due to kerosene poisoning

aspiration pneumonia ,pulmonary oedema

Aspiration pneumonia ,with ingestion of paraffin

aspiration pneumonia 2 degree kerosene

Aspiration Pneumonia AND paraffin poisoning

ASPIRATION PNEUMONIA DUE TO KEROSENE POISONING

aspiration pneumonia due to kerosine poisoning

Aspiration pneumonia due to paraffin ingestion

Aspiration Pneumonia due to Paraffin ingestion

ASPIRATION PNEUMONIA DUE TO POISONING

aspiration pneumonia IN A cp patient

aspiration pneumonia, ABM

aspiration pneumonia, chemical pneumonitis

aspiration pneumonia, choking

aspiration pneumonia, convulsive disorder, tetanus

Aspiration Pneumonia, Delayed milestone

aspiration pneumonia, paraffin ingestion

aspiration pneumonia,hydrocarbon pneumonia

aspiration pneumonia,kerosine poisoing

aspiration pneumonia,partially treated malaria

aspiration pneumonia/drowning

Aspiration pneumonia

aspirational pneumonia

aspiraton pneumonia

aspiraton pneumonia.choking

Aspriation pneumonia

Bacterial meningitis, aspiration pneumonia

Broncho pneumonia

Bronhopneumonia in ashtmatic patient

Chemical pneumonia

chemical pneumonia, hydrocarbon poisoningparaffin

chemical pneumonia, paraffin ingestion

Hypovolemic shock/Pneumonia(Asipiration)GERD

INHALATION PNEUMONIA

Kerosine Ingestion, Aspiration Pneumonia

kerosine poisoing,aspiration pneumonia

kerosine poisoning,aspiration pneumonia

Klebsiella pneumonia

late onset neonatal sepsis. aspiration pneumonia

Lobar pneumonia

Lobar Pneumonia

LOBOR PNEUMONIA

neonatal pneumonia

non resolved pneumonia

non severe pneumonia due to kerosene ingestion

NOSOCOMIAL PNEUMONIA

Organophosphate poisoning,Aspiration pneumonia

Paraffin ingestion , Aspiration Pneumonia

paraffin poisoning,Aspiration pneumonia

PARRAFIN POISONING(ASPIRATION PNEUMONIA)

PCP

PCP in known ISS in HAART

pneumonia and non bloody diahrroea

pneumonia,meningitis

pneumonitis due to kerosene ingestion

PTB/PCP

pulmonary tubeclosis,atypical pneumonia

Recurrent Pneumonia

svere broncho pneumonia

TUBERCULOUS PNEUMONIA

Diagnosis 2: other 1:

Broncho pneumonia

PCP

Diagnosis 2: other 2:

Broncho pneumonia

PCP

Diagnosis 2: other 4:

aspiraion pneumonia

Aspiration Pneumonia

aspiration pneumonia

Aspition pneumonia

B05.2,Measles complicated by pneumonia (J17.1*)

B20.6,PCP /PJP

J18.0,Broncho pneumonia

J18.0,Bronchopneumonia, unspecified

J69.0 aspiration pneumonia

J69.0Aspiration pneumonia

pcp

pneumonia aspiration

Diagnosis 2: other 3:

B20.6,HIV disease resulting in Pneumocystis carinii pneumonia

B20.6,PCP /PJP

Diagnosis 2: other 3 written in free text:

aspiration pneumonia

Aspiration pneumonia

B20.6,PCP /PJP

K12.1,Other forms of stomatitis. B20.6 PCP/PJC

Kerosene Ingestion, Aspiration Pneumonia, Epileptic pt

Lobar Pneumonia

PCP

PCP in sero -reactive

PNEUMONIA

severe aspiration pneumonia.parrafin poisoning

severe malaria with severe pneumonia

Diagnosis malaria:

Malaria test result:

Positive

Diagnosis 1: malaria

Non Classified

Non Severe

Severe

Diagnosis 1: malaria severe:

Severe malaria(clinical malaria-No parasites documented)[ICD10: B54.8]

Severe malaria(P.falciparum documeted)[ICD10: B50.8]

Severe malaria(Parasitological confirmation-no species)[ICD10: B53.8]

Diagnosis 1: malaria non severe:

Non Severe malaria(clinical malaria-No parasites documented)[ICD10: B54.7]

Non Severe malaria(P.falciparum documeted)[ICD10: B50.7]

Non Severe malaria(Parasitological confirmation-no species)[ICD10: B53.7]

Diagnosis 1: malaria no class:

Non Classfied malaria(clinical malaria-No parasites documented)[ICD10: B54.9]

Non Classfied malaria(P.falciparum documeted)[ICD10: B50.9]

Non Classfied malaria(Parasitological confirmation-no species)[ICD10: B53.9]

Diagnosis 2: malaria:

Non Classified

Non Severe

Severe

Diagnosis 2: malaria severe:

Severe malaria(clinical malaria-No parasites documented)[ICD10: B54.8]

Severe malaria(P.falciparum documeted)[ICD10: B50.8]

Severe malaria(Parasitological confirmation-no species)[ICD10: B53.8]

Diagnosis 2: malaria non severe:

Non Severe malaria(clinical malaria-No parasites documented)[ICD10: B54.7]

Non Severe malaria(P.falciparum documeted)[ICD10: B50.7]

Non Severe malaria(Parasitological confirmation-no species)[ICD10: B53.7]

Diagnosis 2: malaria no class:

Non Classfied malaria(clinical malaria-No parasites documented)[ICD10: B54.9]

Non Classfied malaria(P.falciparum documeted)[ICD10: B50.9]

Non Classfied malaria(Parasitological confirmation-no species)[ICD10: B53.9]

Diagnosis 1: other 3

B50.0, Cerebral malaria

B54 Unspecified malaria

Diagnosis 1: other 3 written in free text:

acute bacterial menengitis, celebral malaria

ACUTE GASTRITIS,malaria

aspiration pneumonia,partially treated malaria

black water fever, complicated malaria

CELEBRAL MALARIA INFECTIOUS G.E

celebral maleria/T.F

Cerebral malaria

cerebral malaria

Cerebral malaria, dermatitis

clinical malaria

clinical malaria in a known RVD

clinically s. malaria

complicated malaria

complicated malaria, acute bacterial menengitis

Hyperreactive malarial syndrome

Lower respiratory tract infection, partially treated malaria

malaria fever

malaria fever, warm infestation

malaria in a known sickler

partially treated malaria

partially treated malaria in seroexposed patient

partially treated malaria with allergie RTI

partially treated malaria with gastritis

partially treated malaria, ostiomylitis

partially treated malaria, PTB

partially treated malaria, salmonelosis typhoid fever

partially treated severe malaria

poorly treated malaria

poorly treated malaria, UTI

septicamia, cliniical malaria

shock in severe malaria

uncomplicated malaria

uncomplicated malaria, pruritis

with pertially treated malaria

Diagnosis 2: other 4:

B53.8 Other parasitologically confirmed malaria, NEC

Diagnosis 2: other 3 written in free text:

CEREBRAL MALARIA

Intracranial bleed, cerebral malaria

severe malaria with severe pneumonia

***Diagnosis TB*:**

Diagnosis 1: TB:

Yes

Diagnosis 2: TB:

Yes

Diagnosis 1: other 3:

A15.0,Tuberclosis:Pulmonary TB

A15.9,Respiratory tuberculosis unspecified, confirmed bacteriologically and histologically

A16.2,Tuberculosis of lung, without mention of bacteriological or histological confirmation

A16.9 Respiratory tuberculosis unspecified, without mention of bacteriological or histological confirmation

A16.9,Respiratory tuberculosis unspecified, without mention of bacteriological or histological confirmation

A18.0,Tuberculosis of bones and joints

A18.3,Tuberclosis:Tuberculosis peritonitis

A18.8,Tuberclosis:Extra pulmonary TB

A18.8,Tuberculosis of other specified organs

ASPIRATION OF TB

Diagnosis 1: other 4:

A15.0,Tuberclosis:Pulmonary TB

A16.2,Tuberculosis of lung, without mention of bacteriological or histological confirmation

A16.9,Respiratory tuberculosis unspecified, without mention of bacteriological or histological confirmation

A19.8,Other miliary tuberculosis

Diagnosis 1: other 3 written in free text:

??PTB

A15.0, Pulmonary Tuberclosis

crytococcal menengitis, orapharyngeal candidiasis, moloscom spongiusum in RDD on anti TBs

Disseminated TB

HIV +ve, PTB IN A KNOWN ISS, HIV WASTING SYDROM

Hypothyroidism,TB Relapse

iss ,ptb

koch's

Lumber Tubercilosis

nephrotis.PTB

pleral effusion .plumonary tubeclosis

post TB fibrosis

PTB

PTB in a knownISS on HAART

PTB, Delayed Milestion

PTB,PEN-ORBOTAL CELLULITIS

PTB. ISS

PTB/PCP

pulmonary TB in sero exposed baby

pulmonary tubeclosis

pulmonary tubeclosis,

pulmonary tubeclosis,atypical pneumonia

pulmonary tubeclosis,pleural effusion

PULMONARY TUBERCULOSIS

pulmonary tuberculosis

Rickets, PTB

RVD on septrin, pulmonary tuberculosis

SEPTICEAMIA,plumonary tubeclosis

severe COPD, pulmonary tuberclosis

spinal lesion/TB spine/GBS

TB ADENITIS

TB adenitis

TB ADENITIS, MALIGNANCY

TB Adenitis,lymphoma

TB in RVD

TB MENINGITIS/ TOXOPLASMOSIS

TB pentonitis

TB relapse

TB SPINE

TB,ISS

tuberculosis

TUBERCULOUS PNEUMONIA

Diagnosis 2: other 4:

A15.0,Tuberclosis:Pulmonary TB

A15.0,Tuberculosis of lung, confirmed by sputum microscopy with or without culture

A15.3,Tuberculosis of lung, confirmed by unspecified means

A16.9,Respiratory tuberculosis unspecified, without mention of bacteriological or histological confirmation

A17.0,Tuberculous meningitis (G01*)

A17.9,TBM

A18,Tuberculosis of other organs

A18.2,Tuberculous peripheral lymphadenopathy

A19,Miliary tuberculosis

Diagnosis 2: other 3:

A15.9,Respiratory tuberculosis unspecified, confirmed bacteriologically and histologically

Diagnosis 2: other 3 written in free text:

A15.0, Pulmonary Tuberclosis

congeultal abnormalities in tb

down syndrome, ptb

MDR TB

MILIARY TB

On TB treatment

PTB

PTB defaulter

PTB patient

PTB.INGUINAL HERNIA

TB

TB Adinitis

TB SPINE/SEPTIC ARTHRITIS

Diagnosis diarrhoea:

Diarrhoea:

Yes

Diagnosis 1: diarrhoea:

Diarrhoea(bloody)[ICD10: A09.8]

Diarrhoea(No classification)[ICD10: A09.9]

Diarrhoea(Non[ICD10: A09.0]

Diagnosis 2: diarrhoea:

Diarrhoea(bloody)[ICD10: A09.8]

Diarrhoea(No classification)[ICD10: A09.9]

Diarrhoea(Non[ICD10: A09.0]

Diagnosis 1: other 3:

A00 Cholera

A00,Cholera

A00.9 Cholera, unspecified

A03,Shigellosis / dysentery

A06,Amoebiasis / dysentery

A06.0 Acute amoebic dysentery

A06.0,Acute amoebic dysentery

A09 Diarrhoea and gastroenteritis of presumed infectious origin

A09,Diarrhoea and gastroenteritis of presumed infectious origin / dysentery

amoeba dysentry

Cholera

desentry

dynsentery

dysentry

Diagnosis 1: other 4:

A00 Cholera

A00 Cholera????

A03,Shigellosis / dysentery

A09 Diarrhoea and gastroenteritis of presumed infectious origin

Cholera

Diagnosis 1: other 3 written in free text:

acute diarrhoea disease

AMOEBIC DYSCENTRY

Amoebic dysenrty

B Dysentry

Bacillary Dysentry

Cholera

diarrhoea

diarroea

Dysentery

dysentery

Dysentry

dysentry

Dysentry in RVD

dysentry,INTUSSUSEPTION

dysetry

non-bloody diarroea

pneumonia and non bloody diahrroea

some dehydration,diarroea,vomiting

tonslitis with acutediarrheadisease

Diagnosis 2: other 4:

A00 Cholera

A00,Cholera

A00.9 Cholera, unspecified

A03,Shigellosis / dysentery

A06,Amoebiasis / dysentery

chlolera

cholera

Diagnosis 2: other 3 written in free text:

Cholera

diarrhoea

dysentery

dysentry

Suspected Cholera

<u>Diagnosis dehydration:</u>

Diagnosis 1: dehydration:

No Classification[ICD10: E86.9]

Severe[ICD10: E86.8]

Some dehydration[ICD10: E86.7]

Shock[ICD10: R57.1]

Diagnosis 2: dehydration:

No Classification[ICD10: E86.9]	Some dehydration[ICD10: E86.7]	
Severe[ICD10: E86.8]	Shock[ICD10: R57.1]	

Diagnosis 1: other 3 written in free text:

some dehydration	some dehydration,diarroea,vomiting	

Diagnosis 2: other 3 written in free text

dehydration,Gastro enterisis	GE with Severe dehydration	resolved dehydration

Diagnosis malnutrition

Diagnosis 1: malnutrition:

Kwashiorkor[ICD10: E40]	Severe[ICD10: E43]	No classification[ICD10: E46]
Marasmus[ICD10: E41]	Marasmus-Kwashiorkor[ICD10: E42]	
moderate[ICD10: E44.0]	Mild[ICD10: E44.1]	

Diagnosis 2: malnutrition:

Kwashiorkor[ICD10: E40]	Severe[ICD10: E43]	No classification[ICD10: E46]
Marasmus[ICD10: E41]	Marasmus-Kwashiorkor[ICD10: E42]	
moderate[ICD10: E44.0]	Mild[ICD10: E44.1]	

Diagnosis 1: other 3:

E46 Unspecified protein-energy malnutrition

Diagnosis 1: other 4:

E46,Unspecified protein-energy malnutrition

Diagnosis 1: other 3 written in free text:

KWASHIOKOR	P.E.M	severe acute malnutrition
malnourished child	PEM	undernutrition
malnutrition	PEM IN KNOWN C.P	undernutrition / delayed milestones
Mild kwashiakoo,known HIV/AIDS	PROTEIN ENERGY MALNUTRITION	underweight (PEM)
milk acute malnutrition	PROTEIN MALNUTRITION	
NUTRITIONAL DEFICIT	S.A.M	

Diagnosis 2: other 4:

E40,Kwashiorkor	E44,Undernutition	R63.6,Insufficient intake of food and water due to self neglect
E44,Protein-energy malnutrition of moderate and mild degree	E46 Unspecified protein-energy malnutrition	

Diagnosis 2: other 3:

E44 Protein-energy malnutrition of moderate and mild degree

Diagnosis 2: other 3 written in free text:

malnutrition

PROTEIN ENERGY MALNUTRITION

MALNUTRITION-MARASM

undernutrition

Diagnosis anaemia:

Diagnosis 1: anaemia:

Anaemia(No classification)[ICD10: D64.9]

Anaemia(Non severe)[ICD10: D64.9A]

Severe Anaemia[ICD10: D64.9B]

Diagnosis 2: anaemia:

Anaemia(No classification)[ICD10: D64.9]

Anaemia(Non severe)[ICD10: D64.9A]

Severe Anaemia[ICD10: D64.9B]

Diagnosis 1: other 1:

Sickle cell disease

Diagnosis 1: other 2:

Sickle cell disease

Diagnosis 1: other 3:

D50 Iron deficiency anaemia

D50.9,Iron deficiency anaemia, unspecified

D57 Sickle-cell disorders

D57,Sickle-cell disorders

D57.0 Sickle-cell anaemia with crisis

D57.0, Sickle cell disease:Painful crisis

D57.0,SICKLE CELL DISEASE: Haemolytic crisis

D57.0,Sickle cell disease:Complication

D57.0,Sickle cell disease:Painful crisis

D57.0,Sickle cell disease:Sickling crisis

D57.0,Sickle-cell anaemia with crisis

D57.1,Sickle cell disease

D57.1,Sickle cell disease:SCD (no crisis)

D57.1,Sickle-cell anaemia without crisis

D57.8,Other sickle-cell disorders

D58.9 Hereditary haemolytic anaemia, unspecified

D64.9 Anaemia, unspecified

D64.9,Anaemia, unspecified

mouthsores/angular cheilitis with mild anaemia

painful crisis in a known sickler not on follow-up

Diagnosis 1: other 4:

D57 Sickle-cell disorders

D57,Sickle-cell disorders

D57.0,SICKLE CELL DISEASE: Haemolytic crisis

D57.0,Sickle cell disease:Painful crisis

D57.0,Sickle-cell anaemia with crisis

D57.1,Sickle cell disease

D57.1,Sickle-cell anaemia without crisis

Diagnosis 1: other 3 written in free text:

Acute chest sydrom, severe symptomatic anaemia

Acute chest sydrome in sickle cell disease

Acute chest sydrome in sickler

Acute chest sydrome sickle cell crisis

acute chest syndrome in a known sickler

Acute chest syndrome in known sickler

acute chest syndrome with painful crisis

acute painful crisis

acute painful crisis in a known sickler, reducable umblical hernia

anaemia

ANAEMIA

Anaemia in a known sickler

brain hermorrhage,painfull crisesin sickle cell disease

cardiac failure in a sickler in crisis

clinical anaemia

D57,Sickle-cell disorders

Dactylitis in sicker

Epistaxis in a sickler

haemolitic crisis

Haemolytic crisis

haemolytic crisis in akwown sickler

HAEMOLYTIC CRISIS IN SCD

haemolytic jaundice

HAMOLYTIC CRISIS

HEMOLYTIC CRISIS IN SCD

hereditary spherocytosis

in a known SCD

in a known sickler

in a known sickler on follow up.

in a sickle cell disease patient

in a sickler

in a sickler not on follow up

in crisis

in SCD

in sicle cell disease

known sickler

KNOWN SICKLER IN CRISIS

known sickler in crisis

KNOWN SICKLER IN SCD PAINFUL CRISIS

known sickler on painful crisis

malaria in a known sickler

Mild Anaemia, Meningitis ,electrolyte imbalance

moderate anaemia in a known sickler

moderate I D A

nephrotic syndrome in a known sickler

newly diagnosed SCD

painful corsis

PAINFUL CRISIS

painful crisis

Painful Crisis

painful crisis in a known sickler

Painful crisis in a known sickle cell disease

Painful crisis in a known sickler

painful crisis in a known sickler

painful crisis in a known sickler a septic wound

painful crisis in a known sickler on follow up

PAINFUL CRISIS IN A KNOWN SICKLER WITH MOUTH SORES

painful crisis in a sickler

PAINFUL CRISIS IN SCD

PAINFUL CRISIS in SCD

painful crisis in SCD

PAINFUL CRISIS IN SICKLE CELL

painful crisis in sickle cell disease

painful crisis in sickle cell disease, septicamia

PAINFUL CRISIS IN SICKLER

Painful crisis in sickler

Painful crisis in sickler,urti

PAINFUL CRISIS SCD

PAINFUL CRISIS SICKLE CELL DISEASE

painful crisis with anaemia

painful crisis/anaemia in sickle cell disease

painful haemolytic crisis

SCD

SCD IN CRISIS

SCD IN PAINFUL CRISIS

SCD(PAINFUL CRISIS)

septicamia in a knewly diagnosed sickler, acute chest syndrome

septicamia in a known sickler

septicamia, splenic crisis in a known sickler

seqquestration crisis in a known sicler, upper G I

severe anaemia

severe anaemia in painful crisis, sepsis

sickle cell anaemia

sickle cell anemia

sickle cell crisis

sickle cell crisis(hemolytic)

sickle cell disease

SICKLE CELL DISEASE

sickling crisis

splenic sequastiation srisis in a sickler

vasoclusive crisis/hepatitis/cholecytitis/cholangitis

Vaso-occlusive in sickler

vasso-oclusive crisis is known sickler

Diagnosis 2: other 1:

Sickle cell disease

Diagnosis 2: other 2:

Sickle cell disease

Diagnosis 2: other 4:

D50.9 Iron deficiency anaemia, unspecified

D57 Sickle-cell disorders

D57,Sickle-cell disorders

D57.0 Sickle-cell anaemia with crisis

D57.0,SICKLE CELL DISEASE: Haemolytic crisis

D57.0,Sickle cell disease:Acute Chest Syndrome

D57.0,Sickle cell disease:Painful crisis

D57.0,Sickle cell disease:Sickling crisis

D57.0,Sickle-cell anaemia

D57.0,Sickle-cell anaemia with crisis

D57.1,Sickle cell disease

D57.1,Sickle-cell anaemia without crisis

D64.9,Anaemia, unspecified

Diagnosis 2: other 3:

D57,Sickle-cell disorders

D57.0,Sickle cell disease:Painful crisis

D57.1,Sickle cell disease

Diagnosis 2: other 3 written in free text:

D64.9 Anaemia, unspecified

Dactylitisis in sicker

Epistaxis in a sickler

haemolitic crisis

HEMOLYTIC CRISIS

HEMOLYTIC CRISIS IN SCD

painful and himolytic crisis

PAINFUL CRISIS

painful crisis

PAINFUL CRISIS IN SCD

Painful crisis in sickle cell disease

SCD

SCD IN PAINFUL CRISIS

SCD-HEAMOLYTIC CRISIS

sickle cell anaemia

sickle cell crisis

SICKLE CELL CRISIS(PAINFUL CRISIS)

SICKLE CELLS IN HAEMOLYTIC CRISIS

vassooclusive crisis in sickler

***Diagnosis meningitis*:**

Diagnosis 1: meningitis:

Yes

Diagnosis 2: meningitis:

Yes

Diagnosis 1: other 1:

Neonatal Meningitis

Diagnosis 1: other 3:

A32.1,Listerial meningitis and meningoencephalitis

ABM

G00,Bacterial meningitis, not elsewhere classified

G00.8 Other bacterial meningitis

G00.9,Bacterial meningitis, unspecified

G03.0, Bacterial meningitis

G03.9 Meningitis, unspecified

G03.9,Meningitis, unspecified

G04.2 Bacterial meningoencephalitis and meningomyelitis, NEC

G04.2,Bacterial meningoencephalitis and meningomyelitis, not elsewhere classified

G04.9 meningoemphalitis

G04.9, meningoenphalitis

Diagnosis 1: other 4:

G03.0 Bacterial meningitis

G03.9 Meningitis, unspecified

G04.2,Bacterial meningoencephalitis and meningomyelitis, not elsewhere classified

Diagnosis 1: other 3 written in free text:

ABM

acute bacterial menengitis

acute bacterial menengitis, acute otitis media,

acute bacterial menengitis, celebral malaria

acute bacterial menengitis, skin rush

acute flacial paralysis,ABM

acute tonsolitis,MENENGITIS

aspiration pneumonia, ABM

Bacterial meningitis, aspiration pneumonia

complicated malaria, acute bacterial menengitis

convulsions cause meningitis

Creptococcal meningitis

CRYPTOCCOCAL MENINGITIS

cryptococoal menigitis

crytococcal menengitis, orapharyngeal candidiasis, moloscom spongiusum in RDD on anti TBs

G04.2 Bacterial meningoencephalitis and meningomyelitis, NEC

in a sero exposed child, acute bacterial menengitis

MENENGITIS

Meningocephalitis,Psychiatritic disoder

meningoencephalitis

Meningoencephalitis , Mental retardation

meningoencephalus/GBS

Mild Anaemia, Meningitis ,electrolyte imbalance

pneumonia,meningitis

possible menengitis

probable menengitis

probable menigitis

septic arthiritis,osteomylitis.BM

TB MENINGITIS/ TOXOPLASMOSIS

Diagnosis 2: other 4:

A17.0,Tuberculous meningitis (G01*)

A17.9,TBM

G00 Bacterial meningitis, NEC

G00,Bacterial meningitis, not elsewhere classified

G00.9,Bacterial meningitis, unspecified

G04.2 Bacterial meningoencephalitis and meningomyelitis, NEC

Diagnosis 2: other 3:

G04.2 Bacterial meningoencephalitis and meningomyelitis, NEC

Diagnosis 2: other 3 written in free text:

mengoencephalitis

meningo encephalitis

***Diagnosis asthma*:**

Diagnosis 1: asthma:

Asthma-No classification[ICD10: J45.9]

Asthma-Severe[ICD10: J45.9B]

Asthma-Non severe[ICD10: J45.9A]

Asthma-very severe[ICD10: J46]

Diagnosis 2: asthma:

Asthma-No classification[ICD10: J45.9]

Asthma-Severe[ICD10: J45.9B]

Asthma-Non severe[ICD10: J45.9A]

Asthma-very severe[ICD10: J46]

Diagnosis 1: other 3:

Acute Asthmatic attack

J45 Asthma

J45.9 Asthma, unspecified

Diagnosis 1: other 4:

Status asthmaticus

Diagnosis 1: other 3 written in free text:

Acute asmatic

Acute Asmatic attack

ACUTE ASMATIC ATTACK

Acute asthmatic

acute asthmatic attack

Acute asthmatic attack

acute asthmatic attack

acute exercobation of asthma

acute onset of broncheal asthma

acute tonsilitis in a known asmatic

asthamatic attack

asthma

Asthma exlebation

asthmatic attack

Asthmatic attack

bacterial conjuctivitis in newly diagnosed asthma patient

BRONCHIAL ASTHMA

bronchial asthma

Bronchial asthma

bronchoasthma

bronchola asthma

Bronhopneumonia in ashtmatic patient

CHILDHOOD ASTHMA

in a known asthmatic

in a known asthmatic patient

Recurrent Asthmatic Attack

resolved asthmatic attack

Severe Asmatic attack

STATUS ASTHMATICUS

v.s asthma

Diagnosis 2: other 4:

Acute Asthmatic attack

J45 Asthma

Diagnosis 2: other 3:

Acute Asthmatic attack

Diagnosis 2: other 3 written in free text:

Acute asthmatic attack

acute asthmatic attack

asthmatic attack

brochial asthma

Brocho Asthma

***Diagnosis bronchiolitis*:**

Diagnosis 1: other 1:

Bronchiolitis

Diagnosis 1: other 2:

Bronchiolitis

Diagnosis 1: other 3:

brochiolitis

bronchiolitis

J21 Acute bronchiolitis

J21,Acute bronchiolitis

J21,Bronchiolitis

J21.9 Acute bronchiolitis, unspecified

J21.9,Acute bronchiolitis, unspecified

Diagnosis 1: other 4:

J21,Bronchiolitis

J21.9 Acute bronchiolitis, unspecified

J21.9,Acute bronchiolitis, unspecified

Diagnosis 1: other 3 written in free text:

Bronchiolitis

Broncholitis

Broncholitis

J21.9 Acute bronchiolitis, unspecified

viral bronchiolitis

Diagnosis 2: other 1:

Bronchiolitis

Diagnosis 2: other 2:

Bronchiolitis

Diagnosis 2: other 4:

J21,Acute bronchiolitis

J21,Bronchiolitis

J21.9 Acute bronchiolitis, unspecified

Diagnosis 2: other 3:

J21,Acute bronchiolitis

J21,Bronchiolitis

J21.9 Acute bronchiolitis, unspecified

J21.9,Acute bronchiolitis, unspecified

Diagnosis 2: other 3 written in free text:

bronchiolitis

bronchiolitis ??adenoid hypertrophy

Diagnosis sepsis:

Diagnosis 1: other 1:

Neonatal Sepsis

Diagnosis 1: other 2:

Neonatal Sepsis

Diagnosis 1: other 3:

A41 Other septicaemia

A41,Other septicaemia

A41.50,Sepsis due to unspecified Gram-negative organisms

A41.9 Septicaemia, unspecified

A41.9,Sepsis:Sepsis

A41.9,Sepsis:Septic shock

A41.9,Sepsis:Septicaemia

A41.9,Septicaemia, unspecified

M00,Arthritis:Septic Arthritis

M00,Pyogenic arthritis

O85,Puerperal sepsis

P36.8,Other bacterial sepsis of newborn

P36.9,Bacterial sepsis of newborn, unspecified

P36.9,NEONATAL: Sepsis

R57.2 Septic shock

sepsis

septc artheritis

Septic Scalp Rash

septic arthritis

septic eczema

septic gum

septic pastule

septic rash

septic rashes

septic shock

septic skin lesions

SEPTIC TONSILITIS

septic tonsilitis

septic wound

septicemia

T81.42,Sepsis following a procedure

Diagnosis 1: other 4:

A41 Other septicaemia

A41,Other septicaemia

A41.9 Septicaemia, unspecified

A41.9,Sepsis:Sepsis

A41.9,Sepsis:Septic shock

A41.9,Sepsis:Septicaemia

A41.9,Septicaemia, unspecified

P36.9,Bacterial sepsis of newborn, unspecified

P36.9,NEONATAL: Sepsis

septc rash

Umbilical cord sepsis

Diagnosis 1: other 3 written in free text:

?sepsis

A41.50,Sepsis due to unspecified Gram-negative organisms

A41.9,Sepsis:Sepsis

Acute abdomen? worm infestation R/o septiceamia

ACUTE SEPTIC TONSOLITIS

Allergic dermatitis,septiceamia

cellulitis/septic arthritis

communicating hydrocephalus with Brain sepsis

Conjuctivitis ,septicaemia

Convulsions/Sepsis

cord sepsis

Dermatitis with septic skin rash/exfoliation perineal area

early onset neonatal sepsis

Enteric fever/Septicaemia

febrile convulsions, septicaemia

grug poisoning, septic wound

juvenile arthritis ?? septic athritis

late onset neonatal sepsis

late onset neonatal sepsis. aspiration pneumonia

lymphocytis,septic arthritis

neonatal sepsis

Neonatal sepsis

neonatal sepsis,

Neonatal sepsisi,injection abcess

nephrotic syndrome.septic wound

P36.9,NEONATAL: Sepsis

painful crisis in a known sickler a septic wound

painful crisis in sickle cell disease, septicamia

Post septicaemia

postoperation sepsis

reducable umblical hernia, septiceamia

rt kneee septic athritis/lt2nd phallanx.traumatic swelling

scabies-infected with septicaemia,immunosuppression

sepsi

sepsis

SEPSIS

Sepsis

sepsis myocitis

sepsis??

septic rash

septic rashes

septic shock

SEPTIC AEMIA,SEPTIC SPOTS

septic arthiritis,osteomylitis.BM

septic arthritis

Septic arthritis

septic arthritis with abscess ,cellulitis,osteo myelitis

septic arthtitis

septic artritis/RT thigh absess/acute osteomyrlitis

septic burn

septic cord

septic damaters

septic dermatitis

SEPTIC ECZEMA

Septic occipital sores

septic polyathritis

SEPTIC RASH

septic rash

septic rashes

septic shock

septic skin rash

septic spots

septic superficial burn12%

septic superficial burn14%

Septic tonsolities

Septic tonsolities grade 3

septic tonsolitis

Septic Tonsolitis

SEPTIC UMBLICUS

SEPTIC WOUND

septic wound

Septic wound

Septic wound, Conjuctivitis

septic wounds (vesiculo pustular

Septicaemia

septicaemia

SEPTICAEMIA

septicaemia in a sero-exposed

septicaemia, angula chilitis

SEPTICAEMIA,CONJUCTIVITIS

septicaemia,metabolic acidesis

Septicaemia,Umblical Hernia

SEPTICAEMIA/ACUTE BACTERIAL INFECTION

septicaemia/neonatal pustutosis

septicamia

septicamia in a knewly diagnosed sickler, acute chest syndrome

septicamia in a known sickler

septicamia, cliniical malaria

septicamia, splenic crisis in a known sickler

septiceamia

SEPTICEAMIA

septiceamia and pharyngeal tonsillitis

septiceamia due to bacterial pharyngitis

septiceamia due to pharyngitis tonsillitis

septiceamia with left sided lemparesis

SEPTICEAMIA,plumonary tubeclosis

septiceamia/ Entiric fever

septiceamia/Head/cervical spine injury

septicemia

septiiccircumferentiial

Severe bacterial pharyngitis?septicaemia

severe anaemia in painful crisis, sepsis

severe sepsis

Severe sepsis,Rabies

skin sepsis

tangapenatrius in septic wound

Diagnosis 2: other 1:

Neonatal Sepsis

Diagnosis 2: other 2:

Neonatal Sepsis

Diagnosis 2: other 4:

A41,Other septicaemia

A41.9 Septicaemia, unspecified

A41.9,Sepsis:Sepsis

A41.9,Sepsis:Septic shock

A41.9,Sepsis:Septicaemia

A41.9,Septicaemia, unspecified

M00,Arthritis:Septic Arthritis

P36.8,Other bacterial sepsis of newborn

P36.9,Bacterial sepsis of newborn, unspecified

P36.9,NEONATAL: Sepsis

R57.2 Septic shock

septc rashes

septic papules

septic rashes

septic shock

septic skin lesions

septic sores

T81.42,Sepsis following a procedure

Diagnosis 2: other 3:

A41.9,Sepsis:Sepsis

A41.9,Sepsis:Septicaemia

A41.9,Septicaemia, unspecified

O85,Puerperal sepsis

P36.9,Bacterial sepsis of newborn, unspecified

septic shock

Diagnosis 2: other 3 written in free text:

Dental sepsis/septiceamia

Rhinitis and septic scalp rash

sepsis

Septcaemia

septic rash

septic generalised body postules

septic rash

septic shock

septic skin rash

septic tonsolitis

septic wound

SEPTIC WOUND – HEAD

septicaemia

Septicaemia

septicamia, typhoid fever

septiceamia

septiceamia,parotitis

septiceamia/ AKI

SEPTICEMIA

TB SPINE/SEPTIC ARTHRITIS

Appendix 3.9: R coding

```
## run summary stats for some variables for creating new variables ##

summary(as.factor(hospital_data$age_years))

summary(as.factor(hospital_data$age_mths))

summary(as.factor(hospital_data$length))

hist(hospital_data$length)

----------------------------------------------------------------

## new age_mths_noyears column ##

hospital_data$age_mths_noyears<-hospital_data$age_mths

hospital_data$age_mths_noyears[with(hospital_data,age_years==1|age_years==2|age_years==
3|age_years==4|age_years==5|age_years==6|age_years==7|age_years==8|age_years==9|age_
years==10|age_years==11|age_years==12|age_years==13|age_years==14|age_years==15|age
_years==16|age_years==17|age_years==18)]<-NA

------------------------------------------------------------

## create new columns for admission dates ##

## month

x<-hospital_data$date_adm

z<-as.Date(x,"%m/%d/%Y")

p<-as.POSIXlt(z)

hospital_data$month<-p$mon+1

## year

hospital_data$year<-p$year+1900

## weekend_numbers

hospital_data$weekend_numbers<-p$wday+1

## weekend

hospital_data$weekend<-
(hospital_data$weekend_numbers==1|hospital_data$weekend_numbers==7)

----------------------------------------------------------------

## diagnoses ##

## Example: pneumonia
```

hospital_data$diagnosis_pneumonia<-(hospital_data$dx1_pneum=="Pneumonia(No classification)[ICD10: J18.9]"|hospital_data$dx1_pneum==

"Pneumonia(Non Severe)[ICD10: J18.9A]"|hospital_data$dx1_pneum=="Pneumonia(severe)[ICD10: J18.9B]"|hospital_data$dx1_pneum==

"Pneumonia(Very severe)[ICD10: J18.9C]"|hospital_data$dx2_pneum=="Pneumonia(No classification)[ICD10: J18.9]"|hospital_data$dx2_pneum==

"Pneumonia(Non Severe)[ICD10: J18.9A]"|hospital_data$dx2_pneum=="Pneumonia(severe)[ICD10: J18.9B]"|hospital_data$dx2_pneum==

"Pneumonia(Very severe)[ICD10: J18.9C]"|hospital_data$dx1_other_1=="Broncho pneumonia"|hospital_data$dx1_other_1=="PCP"|hospital_data$dx1_other_3==

"aspiation pneumonia"|hospital_data$dx1_other_3=="Aspiration Pneumonia"|hospital_data$dx1_other_3=="aspiration pneumonia"|hospital_data$dx1_other_3==

"aspration pneumonia"|hospital_data$dx1_other_3=="B20.6 HIV disease resulting in Pneumocystis carinii pneumonia"|hospital_data$dx1_other_3==

"B20.6,HIV disease resulting in Pneumocystis carinii pneumonia"|hospital_data$dx1_other_3=="B20.6,PCP /PJP"|hospital_data$dx1_other_3==

"B20.6,Pneumocytis pneumonia"|hospital_data$dx1_other_3=="B59,Pneumocystosis"|hospital_data$dx1_other_3==
="B59,Pneumonia carinis Pneumonia"|hospital_data$dx1_other_3==

"Bronchopneumonia"|hospital_data$dx1_other_3=="J17.3 Pneumonia in parasitic diseases"|hospital_data$dx1_other_3=="J18.0,Broncho pneumonia"|hospital_data$dx1_other_3==

"J18.0,Bronchopneumonia, unspecified"|hospital_data$dx1_other_3=="J18.9,Pneumonia, unspecified"|hospital_data$dx1_other_3==

"J69.0 Aspiration pneumonia"|hospital_data$dx1_other_3=="J69.0, ASPIRATION PNEUMONIA"|hospital_data$dx1_other_3=="J69.0, Aspiration Pneumonia"|hospital_data$dx1_other_3==

"J69.0Aspiration pneumonia"|hospital_data$dx1_other_3=="O74.0,Aspiration pneumonitis due to anaesthesia during labour and delivery"|hospital_data$dx1_other_3==

"P36.8,NEONATAL: Pneumonia"|hospital_data$dx1_other_4=="aspiration pneumonia"|hospital_data$dx1_other_4=="aspiraton pneumonia"|hospital_data$dx1_other_4==

"B20.6,HIV disease resulting in Pneumocystis carinii pneumonia"|hospital_data$dx1_other_4=="B20.6,PCP /PJP"|hospital_data$dx1_other_4==

"B20.6,Pneumocytis pneumonia"|hospital_data$dx1_other_4=="chemical pneumonia"|hospital_data$dx1_other_4=="inhalatonal pneumonia"|hospital_data$dx1_other_4==

"J18.0 Bronchopneumonia, unspecified"|hospital_data$dx1_other_4=="J18.0,Bronchopneumonia, unspecified"|hospital_data$dx1_other_4==

"J69.0 Aspiration pneumonia"|hospital_data$dx1_other_3_text=="aspiartion pneumonia secondary to paraffin ingestion"|hospital_data$dx1_other_3_text==

"aspiartion pneumonia, paraffin poisoning"|hospital_data$dx1_other_3_text=="Aspiration pneumonia"|hospital_data$dx1_other_3_text=="aspiration pneumonia"|hospital_data$dx1_other_3_text==

"ASPIRATION PNEUMONIA"|hospital_data$dx1_other_3_text=="Aspiration Pneumonia"|hospital_data$dx1_other_3_text==

"Aspiration Pneumonia due to kerosene poisoning"|hospital_data$dx1_other_3_text=="aspiration pneumonia ,pulmonary oedema"|hospital_data$dx1_other_3_text==

"Aspiration pneumonia ,with ingestion of paraffin"|hospital_data$dx1_other_3_text=="aspiration pneumonia 2 degree kerosene"|hospital_data$dx1_other_3_text==

"Aspiration Pneumonia AND paraffin poisoning"|hospital_data$dx1_other_3_text=="ASPIRATION PNEUMONIA DUE TO KEROSENE POISONING"|hospital_data$dx1_other_3_text==

"aspiration pneumonia due to kerosine poisoning"|hospital_data$dx1_other_3_text=="Aspiration pneumonia due to paraffin ingestion"|hospital_data$dx1_other_3_text==

"Aspiration Pneumonia due to Paraffin ingestion"|hospital_data$dx1_other_3_text=="ASPIRATION PNEUMONIA DUE TO POISONING"|hospital_data$dx1_other_3_text==

"aspiration pneumonia IN A cp patient"|hospital_data$dx1_other_3_text=="aspiration pneumonia, ABM"|hospital_data$dx1_other_3_text==

"aspiration pneumonia, chemical pneumonitis"|hospital_data$dx1_other_3_text=="aspiration pneumonia, choking"|hospital_data$dx1_other_3_text==

"aspiration pneumonia, convulsive disorder, tetanus"|hospital_data$dx1_other_3_text=="Aspiration Pneumonia, Delayed milestone"|hospital_data$dx1_other_3_text==

"aspiration pneumonia, paraffin ingestion"|hospital_data$dx1_other_3_text=="aspiration pneumonia,hydrocarbon pneumonia"|hospital_data$dx1_other_3_text==

"aspiration pneumonia,kerosine poisoing"|hospital_data$dx1_other_3_text=="aspiration pneumonia,partially treated malaria"|hospital_data$dx1_other_3_text==

"aspiration pneumonia/drowning"|hospital_data$dx1_other_3_text=="Aspiration pnuemonia"|hospital_data$dx1_other_3_text==

"aspirational pneumonia"|hospital_data$dx1_other_3_text=="aspiraton pneumonia"|hospital_data$dx1_other_3_text=="aspiraton pneumonia.choking"|hospital_data$dx1_other_3_text==

"Aspriation pneumonia"|hospital_data$dx1_other_3_text=="Bacterial meningitis, aspiration pneumonia"|hospital_data$dx1_other_3_text==

"Broncho pneumonia"|hospital_data$dx1_other_3_text=="Bronhopneumonia in ashtmatic patient"|hospital_data$dx1_other_3_text=="Chemical pneumonia"|hospital_data$dx1_other_3_text==

"chemical pneumonia, hydrocarbon poisoningparaffin"|hospital_data$dx1_other_3_text=="chemical pneumonia, paraffin ingestion"|hospital_data$dx1_other_3_text==

"Hypovolemic shock/Pneumonia(Asipiration)GERD"|hospital_data$dx1_other_3_text=="INHALATION PNEUMONIA"|hospital_data$dx1_other_3_text==

"Kerosine Ingestion, Aspiration Pneumonia"|hospital_data$dx1_other_3_text=="kerosine poisoing,aspiration pneumonia"|hospital_data$dx1_other_3_text==

"kerosine poisoning,aspiration pneumonia"|hospital_data$dx1_other_3_text=="Klebsiella pneumonia"|hospital_data$dx1_other_3_text==

"late onset neonatal sepsis. aspiration pneumonia"|hospital_data$dx1_other_3_text=="Lobar pneumonia"|hospital_data$dx1_other_3_text=="Lobar Pneumonia"|hospital_data$dx1_other_3_text==

"LOBOR PNEUMONIA"|hospital_data$dx1_other_3_text=="neonatal pneumonia"|hospital_data$dx1_other_3_text=="non resolved pneumonia"|hospital_data$dx1_other_3_text==

"non severe pneumonia due to kerosene ingestion"|hospital_data$dx1_other_3_text=="NOSOCOMIAL PNEUMONIA"|hospital_data$dx1_other_3_text==

"Organophosphate poisoning,Aspiration pneumonia"|hospital_data$dx1_other_3_text=="Paraffin ingestion , Aspiration Pneumonia"|hospital_data$dx1_other_3_text==

"paraffin poisoning,Aspiration pneumonia"|hospital_data$dx1_other_3_text=="PARRAFIN POISONING(ASPIRATION PNEUMONIA)"|hospital_data$dx1_other_3_text==

"PCP"|hospital_data$dx1_other_3_text=="PCP in known ISS in HAART"|hospital_data$dx1_other_3_text=="pneumonia and non bloody diahrroea"|hospital_data$dx1_other_3_text==

"pneumonia,meningitis"|hospital_data$dx1_other_3_text=="pneumonitis due to kerosene ingestion"|hospital_data$dx1_other_3_text=="PTB/PCP"|hospital_data$dx1_other_3_text==

```
"pulmonary tubeclosis,atypical pneumonia"|hospital_data$dx1_other_3_text=="Recurrent
Pneumonia"|hospital_data$dx1_other_3_text==

"svere broncho pnumonia"|hospital_data$dx1_other_3_text=="TUBERCULOUS
PNEUMONIA"|hospital_data$dx2_other_1=="Broncho
pneumonia"|hospital_data$dx2_other_1==

"PCP"|hospital_data$dx2_other_2=="Broncho
pneumonia"|hospital_data$dx2_other_2=="PCP"|hospital_data$dx2_other_4=="aspiraion
pnuemonia"|hospital_data$dx2_other_4==

"Aspiration Pneumonia"|hospital_data$dx2_other_4=="aspiration
pneumonia"|hospital_data$dx2_other_4=="Aspition
pneumonia"|hospital_data$dx2_other_4==

"B05.2,Measles complicated by pneumonia (J17.1*)"|hospital_data$dx2_other_4=="B20.6,PCP
/PJP"|hospital_data$dx2_other_4=="J18.0,Broncho pneumonia"|hospital_data$dx2_other_4==

"J18.0,Bronchopneumonia, unspecified"|hospital_data$dx2_other_4=="J69.0 aspiration
pneumonia"|hospital_data$dx2_other_4=="J69.0Aspiration
pneumonia"|hospital_data$dx2_other_4==

"pcp"|hospital_data$dx2_other_4=="pneumonia
aspiration"|hospital_data$dx2_other_3=="B20.6,HIV disease resulting in Pneumocystis carinii
pneumonia"|hospital_data$dx2_other_3==

"B20.6,PCP /PJP"|hospital_data$dx2_other_3_text=="aspiration
pneumonia"|hospital_data$dx2_other_3_text=="Aspiration
pneumonia"|hospital_data$dx2_other_3_text==

"B20.6,PCP /PJP"|hospital_data$dx2_other_3_text=="K12.1,Other forms of stomatitis. B20.6
PCP/PJC"|hospital_data$dx2_other_3_text==

"Kerosene Ingestion, Aspiration Pneumonia, Epileptic
pt"|hospital_data$dx2_other_3_text=="Lobar
Pneumonia"|hospital_data$dx2_other_3_text=="PCP"|hospital_data$dx2_other_3_text==

"PCP in sero -
reactive"|hospital_data$dx2_other_3_text=="PNEUMONIA"|hospital_data$dx2_other_3_text=
="severe aspiration pneumonia.parrafin poisoning"|hospital_data$dx2_other_3_text==

"severe malaria with severe pneumonia")


## creating antimalarials variable

## malar_inject

hospital_data$malar_inject<-
(hospital_data$quinl1_pres=="Yes"|hospital_data$arte_pres=="Yes"|hospital_data$artemether
=="Yes")

## malar_oral
```

```
hospital_data$malar_oral<-(hospital_data$coart1_pres=="Yes")


------------------------------------------------------------

## to create missing values column ##

hospital_data$missing<-(apply(hospital_data, 1, function(x) sum(is.na(x))))

------------------------------------------------------------

## % of children who obtained pulse oximeter readings for each hospital ##

s<-split(hospital_data,hospital_data$hosp)

sapply(s,function(x)summary(as.factor(x[ ,c("oximetry")])))

------------------------------------------------------------

## summary stats, example ##

## categorical variable

summary(as.factor(hospital_data$month))

hist(hospital_data$month)

prop.table(table(as.factor(hospital_data$month)))*100

## continuous variable

summary(hospital_data$age_years)

hist(hospital_data$age_years)

summary(as.factor(hospital_data$age_years))

prop.table(table(as.factor(hospital_data$age_years)))*100

------------------------------------------------------------

## summary stats for stratifications, example

## method 1

newdataP <- hospital_data[ which(hospital_data$diagnosis_pneumonia=='1'), ]

summary(as.factor(newdataP$oximetry))

## method 2 (can be combined with 1)

s<-split(hospital_data,hospital_data$diagnosis_pneumonia)

sapply(s,function(x)summary(as.factor(x[ ,c("oxygen")])))

sapply(s,function(x)prop.table(table(as.factor(x[ ,c("oximetry_value")]))))*100

------------------------------------------------------------

## to examine summary of missing values per person
```

```
summary(hospital_data$missing)

var(hospital_data$missing)

hist(hospital_data$missing)

prop.table(table(as.factor(hospital_data$missing)))*100

s<-split(hospital_data,hospital_data$six_months)

sapply(s,function(x)summary(x[ ,c("missing")]))

------------------------------------------------------------------------

## complete case

full_data <- na.omit(hospital_data)

nrow(full_data)

summary(full_data$weight_for_age)

summary(as.factor(full_data$antimalarials))

-----------------------------------------------------------------------------------------


## multiple imputation ##


## missingness by variable value (for MAR vs. MNAR analyses)

s<-split(hospital_data,hospital_data$outcome)

sapply(s,function(x)summary(x[ ,c("missing")]))


## Multiple imputation for R1 ##

## Step 1: specify variables as factors

## example:

hospital_data$month<-factor(hospital_data$month)

## Step 2: run imputations

library(mice)

imp<-mice(hospital_data, me = c("polyreg", "polr", "logreg", "polyreg", "pmm", "pmm",
"logreg", "polyreg", "polr", "logreg", "logreg", "logreg", "logreg", "logreg", "logreg", "logreg",
"logreg", "logreg", "logreg", "logreg", "logreg", "logreg", "logreg", "logreg", "logreg", "logreg",
"logreg", "logreg", "logreg", "logreg", "polyreg", "logreg"), m=30)

## can check for which imputation method was used for each variable:

imp$meth
```

```
## Step 3: convert imputations into a dataset

com <- complete(imp, "long", include = TRUE)

com2 <- complete(imp, "long", include = FALSE)

## Step 4: create po_hosp variable

## Step 5: save the imputed datasets

write.csv(com,file="Q1_imp30.csv")

## Step 6: summary statistics to compare with complete cases

summary(com2$variable)


------------------------------------------------------------

## Regressions ##

## R1

## Step 1: multicollinearity

library(car)

fit = glm(as.factor(oximetry) ~ as.factor(hosp) + as.factor(sex) + age_years + weight_for_age +
as.factor(six_months) + as.factor(po_hosp) + as.factor(par) + as.factor(weekend) +
as.factor(fever) + as.factor(cough) + as.factor(breath) + as.factor(vomit_everything) +
as.factor(feed) + as.factor(convulsions) + as.factor(resp) + as.factor(stridor) + as.factor(cyanosis)
+ as.factor(indrawing) + as.factor(grunting) + as.factor(crackles) + as.factor(drink) +
as.factor(wheeze) + as.factor(cap) + as.factor(pallor) + as.factor(neck) + as.factor(font) +
as.factor(oedema) + as.factor(avpu) + as.factor(length), data=com2, family=binomial)

vif(fit)

## Step 2: full model regression

library(mice)

head(hospital_data)

test<-as.mids(hospital_data, .imp=2, .id=3)

fit <- with(test,glm(as.factor(oximetry) ~ as.factor(hosp) + as.factor(sex) + age_years +
weight_for_age + as.factor(six_months) + as.factor(po_hosp) + as.factor(par) +
as.factor(weekend) + as.factor(fever) + as.factor(cough) + as.factor(breath) +
as.factor(vomit_everything) + as.factor(feed) + as.factor(convulsions) + as.factor(resp) +
as.factor(stridor) + as.factor(cyanosis) + as.factor(indrawing) + as.factor(grunting) +
as.factor(crackles) + as.factor(drink) + as.factor(wheeze) + as.factor(cap) + as.factor(pallor) +
as.factor(neck) + as.factor(font) + as.factor(oedema) + as.factor(avpu) + as.factor(length) +
as.factor(avpu):as.factor(cyanosis) + as.factor(avpu):as.factor(grunting) +
as.factor(avpu):as.factor(feed) + as.factor(cyanosis):as.factor(grunting) +
as.factor(cyanosis):as.factor(feed) + as.factor(grunting):as.factor(feed) +
```

```
as.factor(indrawing):as.factor(cyanosis) + as.factor(indrawing):as.factor(grunting) +
as.factor(indrawing):as.factor(feed) + as.factor(indrawing):as.factor(avpu) +
as.factor(resp):as.factor(avpu) + as.factor(resp):as.factor(cyanosis) +
as.factor(resp):as.factor(grunting) + as.factor(resp):as.factor(feed) +
as.factor(resp):as.factor(indrawing), family=binomial))

est<-pool(fit)

summary(est)



----------

## aic method for Q1

library(mice)

mat<-complete(imp, 30)

## create po_hosp

## aic

library(MASS)

mod_base = (glm(as.factor(oximetry) ~ as.factor(hosp) + as.factor(sex) + age_years +
weight_for_age + as.factor(six_months) + as.factor(po_hosp) + as.factor(par), data = mat,  family
= binomial))

mod_nxt = update(mod_base, .~.-+ as.factor(weekend) + as.factor(fever) + as.factor(cough) +
as.factor(breath) + as.factor(vomit_everything) + as.factor(feed) + as.factor(convulsions) +
as.factor(resp) + as.factor(stridor) + as.factor(cyanosis) + as.factor(indrawing) +
as.factor(grunting) + as.factor(crackles) + as.factor(drink) + as.factor(wheeze) + as.factor(cap) +
as.factor(pallor) + as.factor(neck) + as.factor(font) + as.factor(oedema) + as.factor(avpu) +
as.factor(length))

mod_stp = stepAIC(mod_nxt, scope = list(upper = ~ as.factor(hosp) + as.factor(sex) + age_years +
weight_for_age + as.factor(six_months) + as.factor(po_hosp) + as.factor(par) +
as.factor(weekend) + as.factor(fever) + as.factor(cough) + as.factor(breath) +
as.factor(vomit_everything) + as.factor(feed) + as.factor(convulsions) + as.factor(resp) +
as.factor(stridor) + as.factor(cyanosis) + as.factor(indrawing) + as.factor(grunting) +
as.factor(crackles) + as.factor(drink) + as.factor(wheeze) + as.factor(cap) + as.factor(pallor) +
as.factor(neck) + as.factor(font) + as.factor(oedema) + as.factor(avpu) + as.factor(length) +
as.factor(avpu):as.factor(cyanosis) + as.factor(avpu):as.factor(grunting) +
as.factor(avpu):as.factor(feed) + as.factor(cyanosis):as.factor(grunting) +
as.factor(cyanosis):as.factor(feed) + as.factor(grunting):as.factor(feed) +
as.factor(indrawing):as.factor(cyanosis) + as.factor(indrawing):as.factor(grunting) +
as.factor(indrawing):as.factor(feed) + as.factor(indrawing):as.factor(avpu) +
as.factor(resp):as.factor(avpu) + as.factor(resp):as.factor(cyanosis) +
as.factor(resp):as.factor(grunting) + as.factor(resp):as.factor(feed) +
as.factor(resp):as.factor(indrawing),
```

lower = ~ as.factor(hosp) + as.factor(sex) + age_years + weight_for_age + as.factor(six_months) + as.factor(po_hosp) + as.factor(par),

trace = FALSE))

Bootstrap AIC

Q1

library(MASS)

library(bootStepAIC)

create po_hosp

Bootstrap AIC

fitQ1 <- glm(as.factor(oximetry) ~ as.factor(hosp) + as.factor(sex) + age_years + weight_for_age + as.factor(six_months) + as.factor(po_hosp) + as.factor(par) + as.factor(weekend) + as.factor(fever) + as.factor(cough) + as.factor(breath) + as.factor(vomit_everything) + as.factor(feed) + as.factor(convulsions) + as.factor(resp) + as.factor(stridor) + as.factor(cyanosis) + as.factor(indrawing) + as.factor(grunting) + as.factor(crackles) + as.factor(drink) + as.factor(wheeze) + as.factor(cap) + as.factor(pallor) + as.factor(neck) + as.factor(font) + as.factor(oedema) + as.factor(avpu) + as.factor(length) + as.factor(avpu):as.factor(cyanosis) + as.factor(avpu):as.factor(grunting) + as.factor(avpu):as.factor(feed) + as.factor(cyanosis):as.factor(grunting) + as.factor(cyanosis):as.factor(feed) + as.factor(grunting):as.factor(feed) + as.factor(indrawing):as.factor(cyanosis) + as.factor(indrawing):as.factor(grunting) + as.factor(indrawing):as.factor(feed) + as.factor(indrawing):as.factor(avpu) + as.factor(resp):as.factor(avpu) + as.factor(resp):as.factor(cyanosis) + as.factor(resp):as.factor(grunting) + as.factor(resp):as.factor(feed) + as.factor(resp):as.factor(indrawing), data=hospital_data, family=binomial)

boot.stepAIC(fitQ1, hospital_data, B = 30, alpha = 0.05, scope = list(upper = ~ as.factor(hosp) + as.factor(sex) + age_years + weight_for_age + as.factor(six_months) + as.factor(po_hosp) + as.factor(par) + as.factor(weekend) + as.factor(fever) + as.factor(cough) + as.factor(breath) + as.factor(vomit_everything) + as.factor(feed) + as.factor(convulsions) + as.factor(resp) + as.factor(stridor) + as.factor(cyanosis) + as.factor(indrawing) + as.factor(grunting) + as.factor(crackles) + as.factor(drink) + as.factor(wheeze) + as.factor(cap) + as.factor(pallor) + as.factor(neck) + as.factor(font) + as.factor(oedema) + as.factor(avpu) + as.factor(length) + as.factor(avpu):as.factor(cyanosis) + as.factor(avpu):as.factor(grunting) + as.factor(avpu):as.factor(feed) + as.factor(cyanosis):as.factor(grunting) + as.factor(cyanosis):as.factor(feed) + as.factor(grunting):as.factor(feed) + as.factor(indrawing):as.factor(cyanosis) + as.factor(indrawing):as.factor(grunting) + as.factor(indrawing):as.factor(feed) + as.factor(indrawing):as.factor(avpu) + as.factor(resp):as.factor(avpu) + as.factor(resp):as.factor(cyanosis) + as.factor(resp):as.factor(grunting) + as.factor(resp):as.factor(feed) + as.factor(resp):as.factor(indrawing),

```
                                        lower = ~ as.factor(hosp) + as.factor(sex) + age_years +
weight_for_age + as.factor(six_months) + as.factor(po_hosp) + as.factor(par),
                                        trace = FALSE))
```

Appendix 4.1: Topic guide before interviews began

For hospital staff where pulse oximeters are used

1. Can you tell me a bit about your role in the process of admitting children to the hospital, and what sort of tasks you do on an average day?

2. How do you try to figure out the diagnosis and disease severity of children admitted to your hospital?

a) Do you use any bedside diagnostic tools to help with this?

b) How do you choose which tool to use?

3. How do you decide when to give oxygen to a child?

a) *if use PO:* What oxygen saturation value would you use to decide whether to give oxygen?

b) *if use PO*: What would you do if the symptoms of the child and the pulse oximeter results were contradictory to each other? How would you decide whether to give oxygen?

c) *if use PO*: Would you ever give oxygen to a child who has an oxygen saturation higher than 90%?

d) *if use PO:* Are there times when you wouldn't give oxygen to a child even if their oxygen saturation value was less than 90%?

e) Which symptoms do you find are most important for deciding whether to give oxygen or not?

f) Which symptoms if any would cause you to not want to give oxygen to a child?

4. What do you think of pulse oximeters?

a) How useful do you think they are?

b) What do you think they add to your clinical assessment, if anything?

c) What do you think they are most useful for?

d) Which children are they most useful for?

e) How easy to use do you think they are?

i) Can you give any examples of situations when you have had difficulty using them?

-With any types of patients?

-In any types of circumstances?

f) Is there any other technique or tool that you prefer to use over pulse oximetry?

5. In what situations do you generally choose to use a pulse oximeter?

a) At what stage of the admissions process?

b) With which children?

c) Based on what symptoms?

6. Why do you use a pulse oximeter in these situations? What do you want the information for?

7. What kind of pulse oximeter do you use? [*a free-standing one, or a portable battery-operated one, or a personal one*]

8. Can you tell me about some situations in which you think it is not necessary or useful to use a pulse oximeter, when assessing diagnosis or illness severity?

9. Do you find you rely more on your clinical impression or on the pulse oximeter, for assessing children when they are first admitted?

a) In which situations might you rely on which?

10. Can you tell me about a time when you wanted to use a pulse oximeter but were not able to?

a) How often does this occur?

b) How has this issue changed over time, if at all?

c) What do you think could help to solve this problem?

d) How do you do things differently when you cannot use a pulse oximeter?

e) What, if anything, changes in the ward when a pulse oximeter is not available for this reason?

f) Could you please tell me about any other equipment that you have similar issues with?

If too busy / too many patients is brought up then can ask the following additional follow up question:

a) How do you decide which children need the pulse oximeter the most?

If not enough pulse oximeters is brought up then can ask the following additional follow up questions:

a) How do you decide which children need the pulse oximeter the most?

b) How many pulse oximeters do you think are necessary?

11. How many pulse oximeters do you have in the ward?

a) How many pulse oximeters do you think are necessary to have in the ward?

12. How often do the pulse oximeters break?

a) What happens to a pulse oximeter when it breaks? What do health workers do with the broken pulse oximeter?

b) [*If sent somewhere*]: where is it sent?

c) How long does it take before the pulse oximeter is fixed?

d) Whose responsibility is it to deal with a broken pulse oximeter?

e) On average, how many pulse oximeters are working on any given day?

13. Can you tell me about any other reasons why you are sometimes not able to use a pulse oximeter when you want to?

14. Here is a graph showing the % of children who health workers used a pulse oximeter with at your hospital each month from September 2014 through February 2016.

a) Why do you think that health workers used pulse oximeters more frequently in [x] month instead of [y] month?

b) Can you remember any specific things that happened that month that might have affected pulse oximeter use?

c) Can you think of things which happen every now and then that might affect whether health workers use pulse oximeters or not, that could explain these changes?

d) Why do you think that pulse oximeter use increased overall over this time period?

c) Were you aware that there is so much variability in pulse oximeter use over time at your hospital?

15. When you do use a pulse oximeter, how do you think the pulse oximeter results affect your opinions or decisions?

a) How about your decisions about diagnosis?

b) How about what you think about the severity of the disease?

c) How about your decisions about treatment?

[[16. When did you first hear about pulse oximetry?

a) What form of training, if any, was provided then?

b) What did you think of pulse oximetry after this introduction?]]

17. How was pulse oximetry introduced in your hospital?

a) Can you tell me about who this was run by at the hospital, regional or national level?

b) What form of training, if any, was provided then?

c) What did you think of pulse oximetry after this introduction?

18. Why do you think pulse oximeters are used at some hospitals but not at others?

[[19. How often do you think other doctors or nurses in your hospital use pulse oximeters?]]

[[20. For what reasons do you think other doctors in your hospital choose to use or not use pulse oximeters?

a) Can you tell me about any situations when you wanted to use a pulse oximeter but another health worker did not think it was necessary, or the other way around?

b) Can you think of any times when another health worker has asked you why you didn't use a pulse oximeter when you didn't?]]

21. How are decisions made at your hospital concerning buying new equipment?

22. How are the pulse oximeters that are available at your hospital funded?

23. Can you please tell me about oxygen availability at your hospital?

a) Can you give me any examples of times when you have wanted to give oxygen to a child but have not been able to for some reason?

b) How was the process of diagnosing and giving treatment different in this situation, if at all?

24. Roughly what proportion of children do you give oxygen to?

a) What proportion of children with pneumonia do you give oxygen to?

25. How do you record things like pulse oximeter use and oxygen provision in the medical records? What do you record? When do you record it?

26. Finally, what do you think could be done to encourage health workers at your hospital to use pulse oximeters with children more often?

Appendix 4.2: Topic guide as it was at the time the last interview was conducted

(bold indicates those to focus on)

1. Can you tell me a bit about your role in the process of admitting children to the hospital, and what sort of tasks you do on an average day?

2. How do you try to figure out the diagnosis and disease severity of children admitted to your hospital?

a) Do you use any diagnostic tools to help with this?

b) How do you choose which tool to use?

3. How do you decide when to give oxygen to a child?

a) Which symptoms do you think suggest that a child needs oxygen?

b) Do you use any diagnostic tools to help decide whether to give oxygen?

c) *if use PO:* What oxygen saturation value would you use to decide whether to give oxygen?

d) *if use 90% threshold*: **Would you ever give oxygen to a child who has an oxygen saturation higher than 90%? // What would you do if a child has an oxygen saturation above 90% but their symptoms suggest that they need oxygen? Would you give them oxygen?**

e) *if use 90% threshold:* **Are there times when you wouldn't give oxygen to a child even if their oxygen saturation value was less than 90%? // What would you do if a child has an oxygen saturation below 90% but their symptoms don't seem to suggest that they need oxygen? Would you give them oxygen?**

4. What do you think of pulse oximeters? For instance, how useful do you think they are?

a) Which children are they most useful for at admission?

b) Are there any children who you think don't need a pulse oximeter reading at admission?

c) How reliable do you think they are?

d) How easy to use are they?

i) Are there ever times when you have difficulty using them?

5. Are there ever any situations when you want to use a pulse oximeter but you're not able to for some reason?

a) How often does this happen?

b) What do you think could help to solve this problem?

c) What do you do if you don't have a pulse oximeter?

d) Could you please tell me about any other equipment that you have similar issues with?

6. If too busy / too many patients / not enough pulse oximeters is brought up then can ask the following additional follow up question:

a) How do you decide which children to use the pulse oximeter with?

7. How many pulse oximeters do you have in the ward?

a) What kind are those? [Monitor? Battery-operated? Handheld?]

b) Do you think this is enough pulse oximeters for the ward?

c) How many do you think would be a good number to have in the ward?

8. How often do the pulse oximeters break?

a) What happens when a pulse oximeter breaks? What's the process for repairing it?

b) [*If sent somewhere*]: where is it sent?

c) How long does it take before the pulse oximeter is fixed?

d) Who is responsible for dealing with a broken pulse oximeter?

e) On average, how many pulse oximeters are working on any given day?

9. How often do pulse oximeter batteries run out?

a) How are they replaced?

b) How long does that take?

10. *If at a hospital where pulse oximeters used between 9/2013 and 2/2016:* **Here is a graph showing the % of children who obtained a pulse oximeter reading at admission at your hospital each month from September 2013 through February 2016.**

a) Why do you think there is so much variability? // Why do you think pulse oximeters are used more often in some months than in others?

b) Why do you think that pulse oximeter use increased overall over this time period?

11. *If at a hospital where pulse oximeters were not used between 9/2013 and 2/2016:* **We looked at pulse oximeter use at admission at different hospitals in Kenya and we found that there**

was a lot of variability: pulse oximeters were used a lot more often in some months than in others, and this was different for different hospitals

a) Why do you think there is so much variability? // Why do you think pulse oximeters are used more often in some months than in others?

12. What's the process if you or someone else in the ward wants to request a new piece of equipment?

a) How long does that take?

b) Who is responsible for doing that?

c) Have you gone through this process?

13. When did you first hear about pulse oximetry?

a) What form of training, if any, was provided then?

b) What did you learn about pulse oximetry then?

14. How was pulse oximetry introduced in your hospital?

a) Was any training provided then?

15. What sort of training on pulse oximeters, if any, has there been since you have been working in this ward?

a) Do you think that more training is necessary?

b) How do you think it would be best for this training to be carried out?

16. Can you please tell me about oxygen availability at your hospital?

a) Can you give me any examples of times when you have wanted to give oxygen to a child but have not been able to for some reason?

b) What do you do if you don't have enough oxygen?

17. Roughly what proportion of children do you give oxygen to?

a) What proportion of children with pneumonia do you give oxygen to?

18. When you use a pulse oximeter or give oxygen, where do you record that information?

19. You've mentioned about how pulse oximeters affect your decision of whether to give oxygen or not; do pulse oximeters also affect you decision of whether to give other treatments, for instance antibiotics?

20. Do you think that there is any difference in care based on the time of day or day of the week, for instance in the day vs. the night, or on weekends vs. weekdays?

21. Finally, what do you think could be done to encourage health workers in your ward to use pulse oximeters with children more often?

Appendix 4.3: Main difficulties associated with recruitment

The main difficulties associated with recruitment

- HCWs were generally very busy; this was particularly the case during ward rounds, which could last several hours, when all HCWs were needed for rounds and so none or at most very few were available for interviews.
    - I found that it was best to ask potential participants for an interview then and there rather than setting a time later in the day or another day to speak, as patterns of busyness were not predictable, and so in several situations, pre-planned interview times fell through.
- At one of the hospitals, HCWs had just returned from a strike, so there were not many patients and therefore many of the HCWs were not in the paediatric ward or otherwise locatable.
- Contacts were sometimes not in the hospital on the day of the interviews because they were for instance ill or at a training session.
- Several potential participants asked if there was a paper questionnaire they could fill in instead and then declined to participate when I said there was not.

Appendix 4.4: ethical approval letters from KEMRI and OXTREC for me to conduct the interviews

KENYA MEDICAL RESEARCH INSTITUTE

P.O. Box 54840-00200 NAIROBI - Kenya
Tel: (254) (020) 2722541, 254 (020) 2713349, 0722-205901, 0733-400003 Fax (254) (020) 2720030
Email: director@kemri.org info@kemri.org Website: www.kemri.org

KEMRI/RES/7/3/1 **July 25, 2016**

TO: **ABIGAIL ENOCH,**
PRINCIPAL INVESTIGATOR

THROUGH: **DR. BENJAMIN TSOFA,**
THE DIRECTOR, CGMR-C,
KILIFI

DIRECTOR
CGMR-C
CENTRE FOR GEOGRAPHIC MEDICINE RESEARCH, COAST

Dear Madam,

RE: **PROTOCOL NO. KEMRI/SERU/CGMR-C/049/3283 (*RESUBMISSION OF INITIAL SUBMISSION*): PULSE OXIMETER USE IN KENYAN HOSPITALS: A QUALITATIVE STUDY OF HEALTH WORKERS' PERSPECTIVES OF THE BARRIERS TO PULSE OXIMETER USE**

Reference is made to your letter dated 11th July, 2016. The KEMRI/Scientific and Ethics Review Unit (SERU) acknowledges receipt of the revised study documents on the 19th July, 2016.

This is to inform you that the Committee notes that the issues raised during the 252nd Committee B meeting of the KEMRI/SERU held on **22nd June, 2016** have been adequately addressed.

Consequently, the study is granted approval for implementation effective this day, **25th July, 2016** for a period of one year. Please note that authorization to conduct this study will automatically expire on **July 24, 2017.** If you plan to continue data collection or analysis beyond this date, please submit an application for continuation approval to SERU by **June 12, 2017**.

You are required to submit any proposed changes to this study to the SERU for review and the changes should not be initiated until written approval from the SERU is received. Please note that any unanticipated problems resulting from the implementation of this study should be brought to the attention of the SERU and you should advise the SERU when the study is completed or discontinued.

You may embark on the study.

Yours faithfully,

for

DR. EVANS AMUKOYE,
ACTING HEAD,
KEMRI/SCIENTIFIC AND ETHICS REVIEW UNIT

RECEIVED
28 JUL 2016
DIRECTOR'S OFFICE

In Search of Better Health

Oxford Tropical Research Ethics Committee

University of Oxford
Research Services, University Offices
Wellington Square, Oxford OX1 2JD
Tel. +44 (0)1865 (2)82106
E-mail: oxtrec@admin.ox.ac.uk

Abigail Enoch
St. Edmund Hall
Queen's Lane
Oxford
OX1 4AR

5 July 2016

Dear Ms. Enoch,

Full Title of Study: Pulse oximeter use in Kenyan hospitals: a qualitative study of health workers' perspectives of the barriers to pulse oximeter use.

OxTREC Reference: 598-16

Thank you for your email of the 29 June 2016, and for your minimal risk application form. Other documents reviewed were:

Documents:	Version:	Date:
Protocol (and appendices)	V2.0	29/06/16

The OxTREC executive team reviewed the above application on the 5 July 2016 and gave approval for this study.

Approval is given for the first five years and is subject to receiving the local ethical approval (if this approval has not yet been received).

Any subsequent changes to the application must be submitted to the Committee as an Amendment. This should include a letter to give the reasons for the proposed modifications and all revised documents with changes tracked.

Please ensure that you submit a completed Annual Report form on every anniversary of this approval and a final End of Study Report. The relevant forms can be found on the OxTREC website: http://www.tropicalmedicine.ox.ac.uk/oxtrec.

Yours sincerely

Mary Warrell

Dr Mary Warrell
OxTREC Chairman

Direct Line Tel: +44 (0)1865 (2)82106
Email: oxtrec@admin.ox.ac.uk
Web: www.admin.ox.ac.uk/rso/

Appendix 4.5: Information sheet

KEMRI Wellcome Trust Research Programme: Patient Information Sheet

Study title: Pulse oximeter use in Kenyan hospitals: a qualitative study of health workers' perspectives of the barriers to pulse oximeter use

Institution	Investigators
Nuffield Department of Population Health, University of Oxford	*Abigail Enoch, Prof Sasha Shepperd*
Nuffield Department of Medicine, University of Oxford; KEMRI – Wellcome Trust Research Programme, Nairobi, Kenya	*Prof Mike English, Jacinta Nzinga*
Department of Paediatrics and Child Health, University of Nairobi	*Prof Grace Irimu, Dr. Jacquie Oliwa*
Warwick Business School, University of Warwick	*Prof Gerry McGivern*

Who is carrying out this study and what is this study about?

This study is being conducted as part of a collaborative project between the University of Oxford, the Kenya Medical Research Institute (KEMRI) Wellcome Trust Research Programme, the Kenya Paediatric Association and the Ministry of Health. KEMRI is a government organization that carries out medical research to find better ways of preventing and treating illness in the future for everybody's benefit. Sometimes research involves only asking questions of patients, their parents, community members or health providers about what they know, feel or do.

In this research, we want to learn more about how health workers determine the diagnosis and disease severity of children admitted to hospitals, by listening to your opinions, and asking you to explain your decision-making process and experiences related to this issue. We would like to hold individual interviews with up to 25 health workers who work with children in Kenyan hospitals.

Why do you want to talk to me and what does it involve?

Given your experience as a health worker working with children in a hospital in Kenya, you can contribute much to our understanding and knowledge of how children are assessed at admission to hospital.

- I would like to ask you a number of questions about how you try to figure out the diagnosis and disease severity of children when they are admitted to the hospital, what medical tools or equipment you use to do this, and how you choose which actions to take.
- If you do not want to answer any of the questions you may say so and I will move on to the next question.

- The interview will take between 30 minutes and one hour. It will take place at a time and place that is convenient for you.
- No-one else but I will be present unless you would like someone else there.
- If you agree, the interview will be recorded using two audio-recorders to assist later in fully writing up the information. No-one will be identified by name in the recording.

Are there any disadvantages or advantages to me of taking part?

The interview will take between 30 minutes to one hour of your time. You are free to stop the discussion or leave the study at any point if you feel this is necessary. You are also free to not answer any question you feel uncomfortable with.

There are no individual benefits to taking part and no reimbursement or payment of any kind will be given. However in talking to us, you will contribute to knowledge of assessment of child admissions that may help other people in Kenya and elsewhere in the future, for example through developing new health policies or informing the design of interventions aimed at assisting health workers in improving care for children.

Who will have access to the information I give?

- Only individuals directly involved with this research will have access to your information. We will not share any information about you or about any other research participant beyond a few individuals directly involved in the study.
- All audio-recordings and interview transcripts will be stored securely on password protected computers only accessible to concerned research staff.
- Audio-recordings will be deleted after the end of the study. Transcripts will be placed in the KEMRI and University of Oxford secure archives for three years and then will be destroyed.
- Every participant will be assigned a unique identifier to preserve anonymity.
- The knowledge gained from this research will be shared in summary form, without revealing individuals' identities, with participants and the hospitals where you work; this summary information may also be presented at seminars or conferences and be submitted to a journal for publication. In all cases, we will only share information in ways that do not reveal individual participants' identities. For example, we will remove information that could identify people, such as their names and where they work, and replace this information with number codes.
- Any future research using information from this study must first be approved by the national expert committee to make sure that the interests of participants and their communities are protected.

Who has allowed this research to take place?

All research at KEMRI has to be approved before it begins by several national and international committees who look carefully at planned work. They must agree that the research is important, relevant to Kenya and follows nationally and internationally agreed research guidelines. This includes ensuring that all participants' safety and rights are respected.

What will happen if I refuse to participate?

All participation in research is voluntary. You are free to decide if you want to take part or not. If you do agree you can change your mind at any time without any consequences.

What if I have any questions?

You are free to ask me any question about this research. If you have any further questions about the study, you are free to contact the research team using the contacts below:

Prof Mike English and Dr. Jacquie Oliwa, KEMRI Wellcome Trust Research Programme, P.O. Box 230, Kilifi. Telephone: 0722 628700 or 0722 203417, 0733 522063, 041 7522063

If you want to ask someone independent anything about this research please contact:

Community Liaison Manager, KEMRI Wellcome Trust Research Programme, P.O. Box 230, Kilifi. Telephone: 041 7522 063, Mobile 0723 342 780 or 0705 154 386

And

The Secretary - KEMRI/Scientific and Ethics Review Unit, P. O. BOX 54840-00200, Nairobi, Tel number: 020 272 2541 Mobile: 0722 205 901 or 0733 400 003

Appendix 4.6: consent form

KEMRI-Wellcome Trust Research Programme consent form for Pulse oximeter use in Kenyan hospitals: a qualitative study of health workers' perspectives of the barriers to pulse oximeter use

I have had the study explained to me. I have understood all that has been read/explained and had my questions answered satisfactorily.

☐ **Yes** *please tick* **I agree to be interviewed**

☐ **Yes** *please tick* **I agree for the interview to be audio-recorded**

I understand that I can change my mind at any stage and it will not affect me or my work in any way.

Signature: _____ **Date:** _____

Participant Name: _____ **Time:** _____
(please print name)

I certify that I have followed the study SOP to obtain consent from the participant. S/he apparently understood the nature and the purpose of the study and consents to participation in the study. S/he has been given opportunity to ask questions which have been answered satisfactorily.

Designee/investigator's signature: _____ **Date** _____

Designee/investigator's name : _____**Time** _____

(Please print name)

THE PARTICIPANT SHOULD NOW BE GIVEN A SIGNED COPY TO KEEP

……

Appendix 4.7: Main ethical factors associated with the interviews

- Taking part in the study and agreeing to be interviewed was entirely voluntary and there was no penalty for declining to participate.
- Participants could choose not to answer any of the questions for any reason and could end the interview at any point for any reason and with no penalty. Participants could also request for their interviews to be deleted, with no record retained.
- Only individuals directly involved with this research have access to participants' information. I will not share any information about participants beyond a few individuals directly involved in the study.
- Participants were given ID codes; only this code, no names or other identifiers, was written for identification on the transcripts; the ID code legend linking names to ID codes was kept in a secure location separate from the transcripts.
- Quotes used in the analysis do not have names or other identifiers that could indicate the identity of the speaker; quotes with very specific information that could identify the speaker were not used.
- Data were securely stored in accordance with the policies of KWTRP and Oxford's Nuffield Department of Population Health; transcripts and recordings of interviews were stored on an encrypted password-protected laptop and an encrypted USB drive; and only named investigators have access to the data.
- Recordings of the interviews and the legend linking names with ID codes will be deleted after the end of the study. Anonymized transcripts will be placed in the secure archives of KWTRP and Oxford University for three years after the end of the study. Any further use of these data will only be allowed with appropriate ethical approval. After this period these transcripts will be destroyed.
- There were no individual benefits to taking part and no reimbursement or payment of any kind was given to participants.
- The cost from this research for the interview participants was the time taken to do the interview; I made every effort to minimise disruption to the work of staff. There were no other costs from this research for the interview participants or hospitals.
- Data from the interviews are only be available to me, to ensure confidentiality of participants. Requests for access to primary data from these interviews by people other than the investigators would be submitted to the KWTRP ethical committee as a first step, who would advise on the need for additional ethical review by the KEMRI Research Ethics Committee.

Appendix 5.1: Descriptive statistics

Variable	Proportions
Pulse oximeter use	Obtained a pulse oximeter reading: 51%
Pulse oximeter value	Had an oxygen saturation value <90%: 11%
Oxygen use	Were prescribed oxygen: 8%
Month of admission	January: 9% of total admissions February: 12% March: 10% April: 8% May: 9% June: 9% July: 7% August: 7% September: 6% October: 8% November: 9% December: 4%
Weekend admission	Admitted on a weekend: 25%
Admission time period	Sept 2013-Feb 2014: 12% of total admissions March 2014-Aug 2014: 29% Sept 2014-Feb 2015: 19% March 2015-Aug 2015: 22% Sept 2015-Feb 2016: 18%
Hospital	Hospital 1: 4,299 admissions (15% of total) Hospital 2: 2,727 (10%) Hospital 3: 3,957 (14%) Hospital 4: 5,734 (21%) Hospital 5: 3,845 (14%) Hospital 6: 3,992 (14%) Hospital 7: 3,360 (12%)
Hospital use of pulse oximeters by admission month	23% of admissions occurred during a month that pulse oximeters were used with 0-20% of children at that particular hospital
	21-50% pulse oximeter use: 21%
	51-80% pulse oximeter use: 37%
	81-100% pulse oximeter use: 19%
Sex	Female: 45%
Age in years	Mean: 2.26 Median: 1 Range 0 - 12
Weight-for-age	Mean: -0.83 Median: -0.63 Range: -10.33 - 22.04
Paediatric Admission Record (PAR) use	No PAR available: 5% PAR present, not used: 6% PAR used: 89%
Length of illness before admission	1 day: 25%

	2 days: 18% 3 days: 20% 4 days: 9% 4+ days: 27%
Fever	Had a fever: 75%
Cough	Had a cough: 58%
Difficulty breathing	Had difficulty breathing: 34%
Vomit everything	Were vomiting everything: 21%
Difficulty feeding	Had difficulty feeding: 34%
Convulsions	Had convulsions: 20%
Very high respiratory rate	Had a very high respiratory rate: 11%
Oedema	Had oedema: 3%
Stridor	Had stridor: 3%
Central cyanosis	Had cyanosis: 1%
Chest indrawing	Had indrawing: 32%
Grunting	Were grunting: 12%
Wheeze	Were wheezing: 7%
Crackles	Had crackles: 22%
Capillary refill	Had a capillary refill >3 seconds: 1%
Pallor	Had pallor: 14%
Lack of alertness	Were not alert: 7%
Difficulty drinking	Had difficulty drinking: 17%
Stiff neck	Had a stiff neck: 3%
Bulging fontanelle	Had bulging fontanelle: 1%
Diagnosis pneumonia	Had pneumonia: 45%
Diagnosis malaria	Had malaria: 28%
Diagnosis TB	Had TB: 2%
Diagnosis diarrhoea	Had diarrhoea: 35%
Diagnosis dehydration	Had dehydration: 20%
Diagnosis malnutrition	Had malnutrition: 10%
Diagnosis anaemia	Had anaemia: 8%
Diagnosis meningitis	Had meningitis: 10%
Diagnosis asthma	Had asthma: 3%
Diagnosis bronchiolitis	Had bronchiolitis: 2%
Diagnosis sepsis	Had sepsis: 2%
Antimalarials	Were given oral antimalarials: 2% Injectable antimalarials: 22% Neither: 75%
Outcome	Alive: 91% Died: 6% Referred: 2% Other: 1%

Appendix 5.2: Each hospital's average level of pulse oximeter use over the study time period

Hospital	% children with whom pulse oximeters used at admission	n child admissions in each hospital
1	52%	4,299
2	21%	2,727
3	47%	3,957
4	42%	5,734
5	75%	3,845
6	44%	3,992
7	74%	3,360
8	14%	5,021
9	13%	7,797
10	14%	3,278
11	1%	3,696
12	0%	3,366
13	0%	1,531
14	7%	4,180
total	29%	56,783

Appendix 5.3: Level of missing data for each variable

Level of missing data	Variable
x < 5%	*Pulse oximeter use*
	Oxygen
	Admission month
	Weekend admission
	Admission time period
	Hospital
	Age
	Sex
	Diagnoses
	Antimalarials
	Outcome
5% ≤ x < 10%	*Pulse oximeter value*
	Weight-for-age
	Length of illness before admission
	Fever
	Cough
	Cyanosis
	Pallor
	Lack of alertness
10% ≤ x < 15%	*Difficulty breathing*
	Vomit everything
	Difficulty feeding
	Convulsions
	Oedema
	Stridor
	Indrawing
	Grunting
	Wheeze
	Crackles
	Stiff neck
	Bulging fontanelle
15% ≤ x < 20%	*Difficulty drinking*
20% ≤ x ≤ 25%	*Paediatric Admissions Record (PAR) availability / use*
	Very high respiratory rate
	Capillary refill

Appendix 5.4: Are children with missing data different than those without missing data?

The descriptive statistics of each variable for children with missing data were compared with those for children without missing data (complete cases), to determine if children with missing data were different than complete cases.

Compared with complete cases, children with missing data were

- Less likely to have a PAR used to record their data (which is not surprising as the PAR promotes more thorough recording of data)
- Less likely to have a pulse oximeter reading taken (likely to be either because presence of the PAR promotes both more thorough data recording and pulse oximeter use, and/or because HCWs who follow guidelines in taking a pulse oximeter reading are also more likely to follow guidelines in data recording)
- More likely to have been admitted in earlier time periods (at earlier time periods, data clerks were less familiar with the CIN system, and HCWs had received less feedback from the CIN)

One must however be cautious in interpreting this, as these three variables are inter-related.

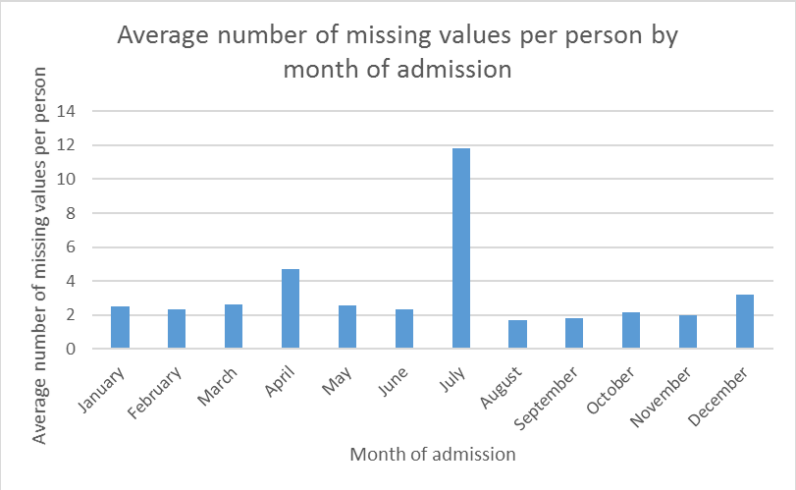
There were more minor differences between children with vs. without missing data for hospital, pallor, pneumonia diagnosis, and malaria diagnosis.

See below for values of the descriptive statistics of children with missing data vs. complete cases for the variables mentioned above in which there was at least a minor difference between values of children with missing data vs. complete cases

Variable	Values	The % of children with missing data with each variable value	The % of complete cases with each variable value
PAR use	No PAR available	11%	1%
	PAR present, not used	11%	<1%
	PAR used	78%	99%
Pulse oximeter use	Pulse oximeter used	42%	64%
Admission time period	Sept 2013-Feb 2014:	20%	<1%
	March 2014-Aug 2014:	40%	11%
	Sept 2014-Feb 2015:	16%	25%
	March 2015-Aug 2015:	13%	37%
	Sept 2015-Feb 2016:	11%	27%
Hospital	Hospital 1	15%	16%
	Hospital 2	10%	10%
	Hospital 3	19%	7%
	Hospital 4	20%	21%
	Hospital 5	12%	17%
	Hospital 6	15%	13%
	Hospital 7	9%	16%
Pallor	Had pallor	16%	12%
Pneumonia diagnosis	Had pneumonia	44%	48%
Malaria diagnosis	Had malaria	30%	25%

Appendix 5.5: Figures and values to determine whether missingness levels were associated with particular values of specific variables, to assess whether the data were likely MAR vs. MNAR

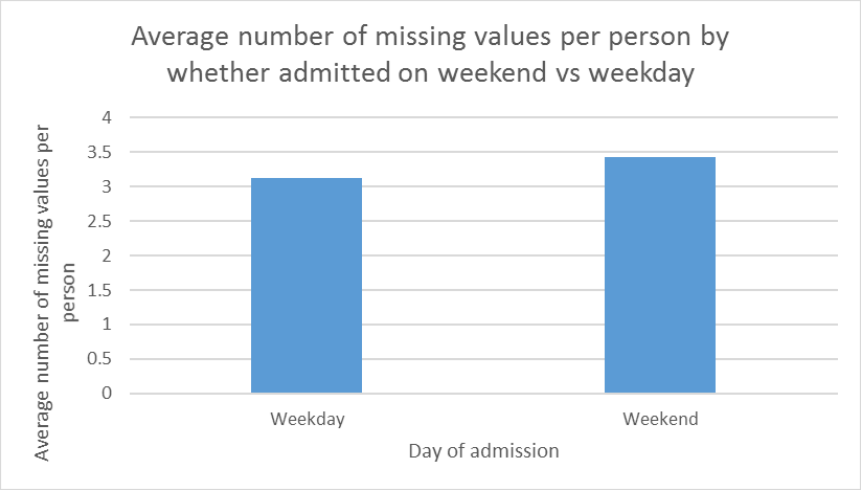
Admission month:



Month	Observed: Average number of missing values per person	Expected: Average number of missing values per person
January	2.5	3.2
February	2.3	3.2
March	2.6	3.2
April	4.7	3.2
May	2.5	3.2
June	2.3	3.2
July	11.8	3.2
August	1.7	3.2
September	1.8	3.2
October	2.2	3.2
November	2.0	3.2
December	3.2	3.2
Total	3.2	

Chi squared value: 0.00457619

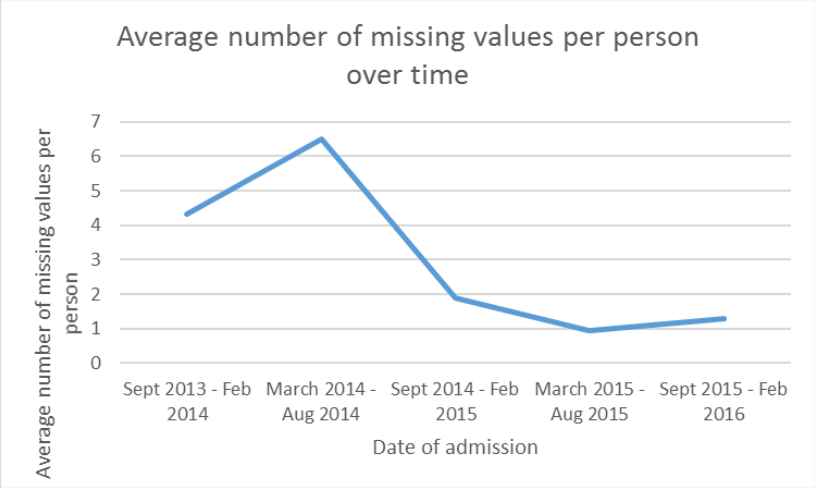
Weekend admission:



Day of admission	Observed: Average number of missing values per person	Expected: Average number of missing values per person
Weekend	3.1	3.2
Weekday	3.4	3.2

Chi squared value: 0.891719

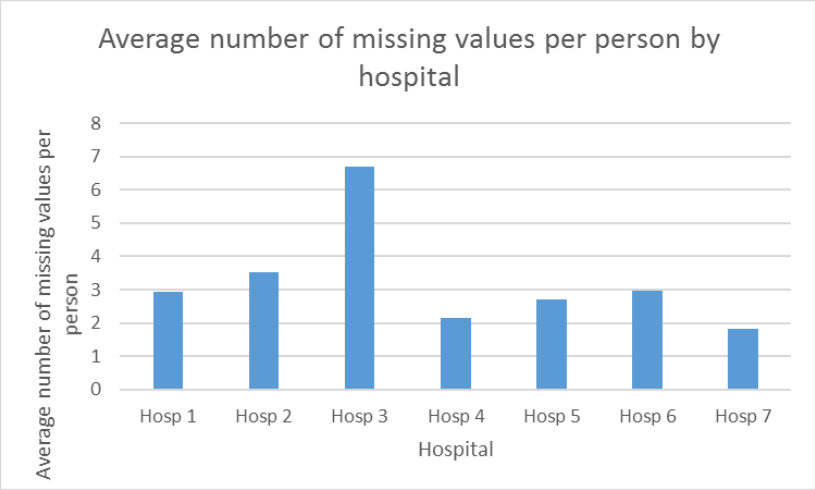
Admission time period:



Time period of admission	Observed: Average number of missing values per person	Expected: Average number of missing values per person
Sept 2013-Feb 2014	4.3	3.2
March 2014-Aug 2014	6.5	3.2
Sept 2014-Feb 2015	1.9	3.2
March 2015-Aug 2015	0.9	3.2
Sept 2015-Feb 2016	1.3	3.2

Chi squared value: 0.133167269

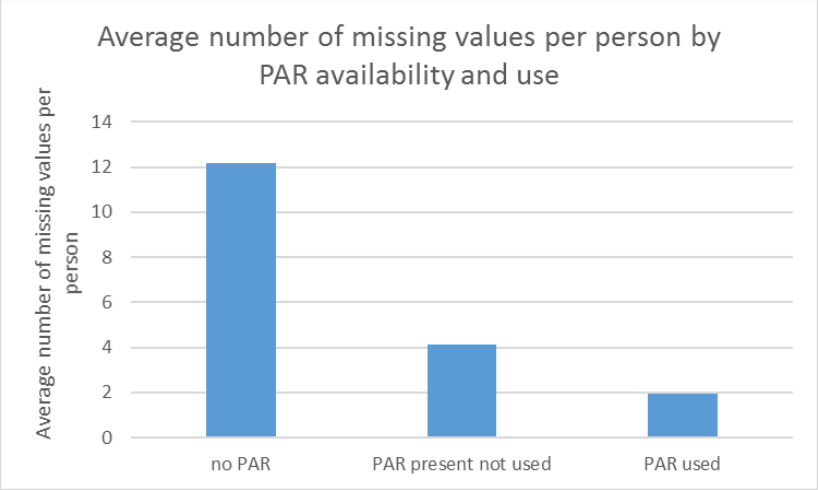
Hospital:



Hospital	Observed: Average number of missing values per person	Expected: Average number of missing values per person
Hospital 1	2.9	3.2
Hospital 2	3.5	3.2
Hospital 3	6.7	3.2
Hospital 4	2.2	3.2
Hospital 5	2.7	3.2
Hospital 6	3.0	3.2
Hospital 7	1.8	3.2

Chi squared value: 0.554441219

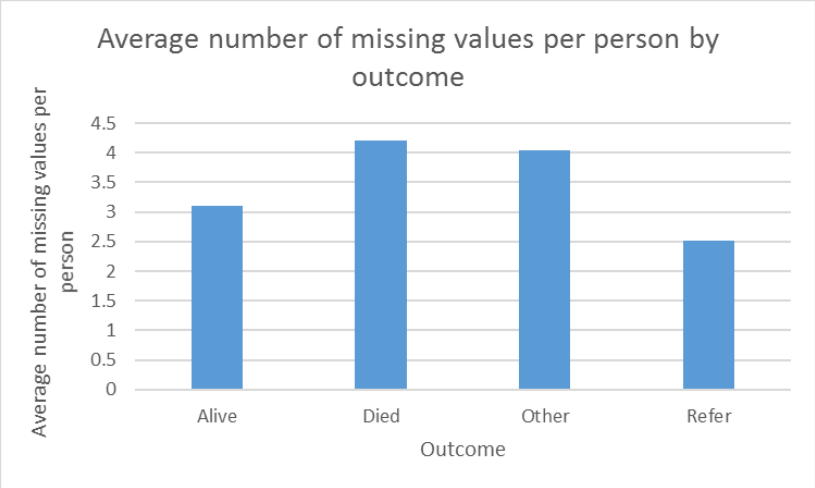
Paediatric Admission Record use:



PAR use	Observed: Average number of missing values per person	Expected: Average number of missing values per person
No PAR available	12.2	3.2
PAR present, not used	4.2	3.2
PAR used	2.0	3.2

Chi squared value: 2.16865 E-06

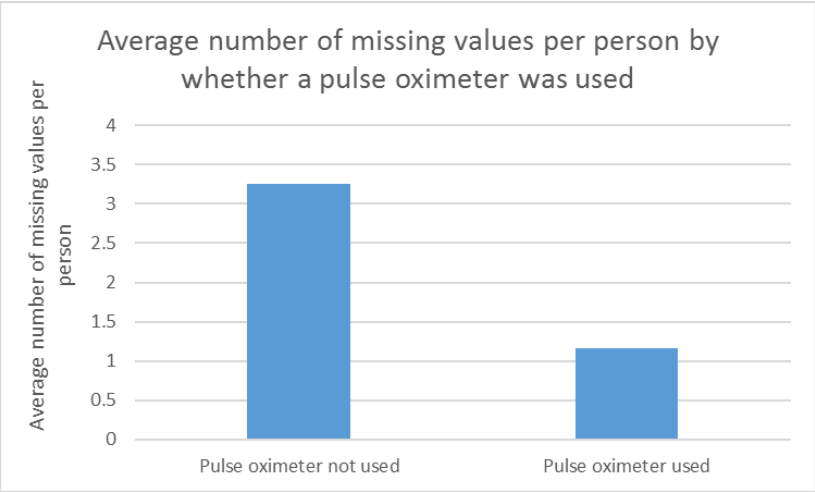
Outcome:



Outcome	Observed: Average number of missing values per person	Expected: Average number of missing values per person
Alive	3.1	3.2
Died	4.2	3.2
Referred	2.5	3.2
Other	4.1	3.2

Chi squared value: 0.875509

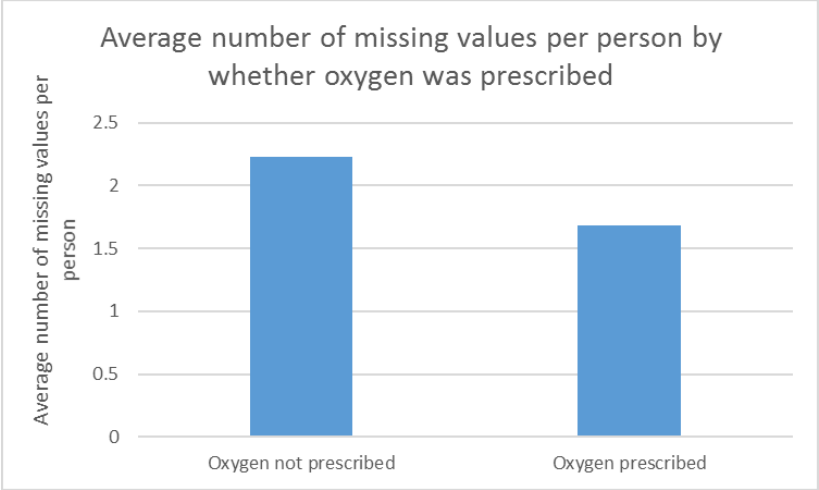
Pulse oximeter use:



Pulse oximeter use	Observed: Average number of missing values per person	Expected: Average number of missing values per person
Pulse oximeter used	1.2	3.2
Pulse oximeter not used	3.3	3.2

Chi squared value: 0.253979321

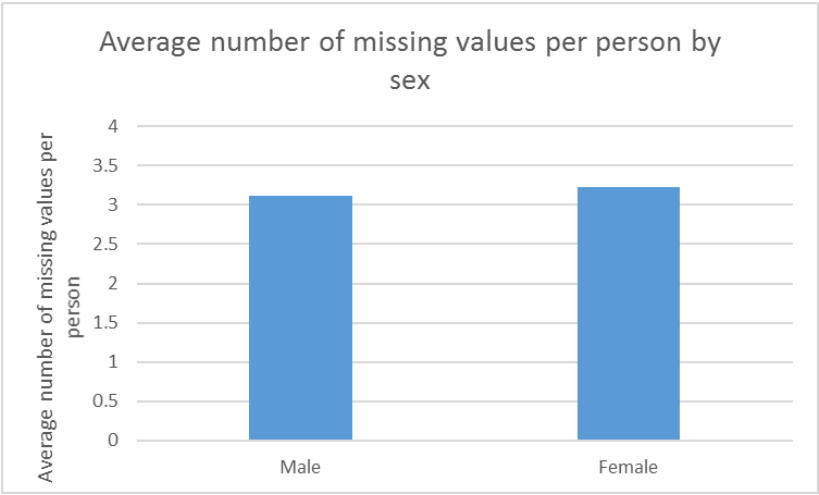
Oxygen use:



Oxygen prescription	Observed: Average number of missing values per person	Expected: Average number of missing values per person
Oxygen prescribed	1.7	3.2
Oxygen not prescribed	2.2	3.2

Chi squared value: 0.313462261

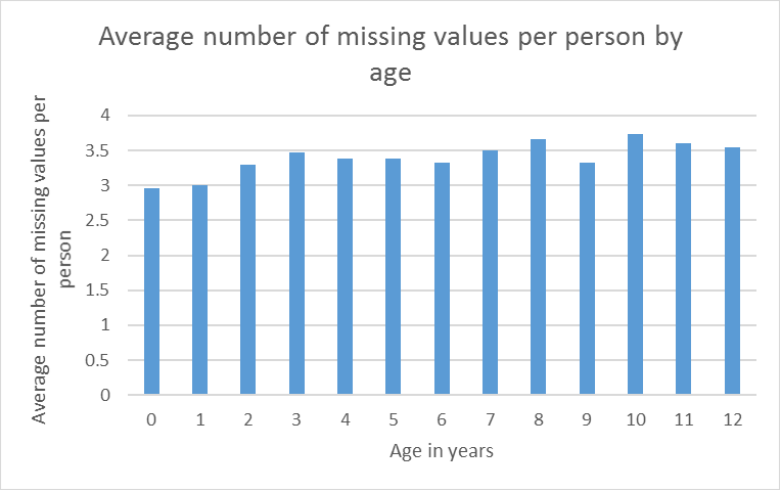
Sex:



Sex	Observed: Average number of missing values per person	Expected: Average number of missing values per person
Female	3.12	3.2
Male	3.2	3.2

Chi squared value: 0.961906

Age:



Age	Average number of missing values per person
1-11 months	3.0
1 year	3.0
2 years	3.3
3 years	3.5
4 years	3.4
5 years	3.4
6 years	3.3
7 years	3.5
8 years	3.7
9 years	3.3
10 years	3.7
11 years	3.6
12 years	3.5

Linear regression, p-value: 0.00128

Appendix 5.6: Comparison of coefficients and confidence intervals when 10 vs. 30 imputations were run

Research question 1: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

Variable value	10 imputations		30 imputations	
	Coefficient	Confidence interval	Coefficient	Confidence interval
Hospital 2	-0.19	-0.35, -0.03	-0.20	-0.35, -0.04
Hospital 3	0.31	0.18, 0.44	0.32	0.19, 0.45
Hospital 4	-0.03	-0.13, 0.07	-0.03	-0.13, 0.06
Hospital 5	0.15	0.02, 0.27	0.15	0.04, 0.27
Hospital 6	-0.06	-0.17, 0.05	-0.05	-0.17, 0.06
Hospital 7	0.25	0.10, 0.39	0.26	0.12, 0.39
Female	-0.01	-0.07, 0.05	-0.01	-0.07, 0.05
Age	-0.02	-0.03, -0.01	-0.02	-0.03, -0.01
Weight-for-age	0.00	-0.02, 0.02	0.01	-0.01, 0.02
March 2014-Aug 2014	0.19	-0.02, 0.40	0.18	-0.04, 0.40
Sept 2014-Feb 2015	0.32	0.07, 0.58	0.32	0.07, 0.56
March 2015-Aug 2015	0.39	0.16, 0.63	0.39	0.15, 0.63
Sept 2015-Feb 2016	0.46	0.22, 0.70	0.45	0.22, 0.69
21-50% pulse oximeter use[i]	2.36	2.20, 2.52	2.35	2.21, 2.50
51-80% pulse oximeter use[i]	3.42	3.24, 3.60	3.42	3.27, 3.57
81-100% pulse oximeter use[i]	4.63	4.44, 4.81	4.63	4.46, 4.79
PAR present not used	1.06	0.59, 1.53	1.06	0.70, 1.42
PAR used	0.87	0.61, 1.14	0.88	0.69, 1.08
Weekend admission	-0.09	-0.16, -0.02	-0.09	-0.16, -0.02
Fever	0.09	0.02, 0.17	0.09	0.02, 0.17
Cough	0.11	0.04, 0.18	0.11	0.04, 0.19
Difficulty breathing	0.12	0.04, 0.20	0.12	0.05, 0.20
Vomit everything	-0.16	-0.25, -0.08	-0.17	-0.25, -0.09
Difficulty feeding	-0.01	-0.10, 0.07	-0.01	-0.10, 0.08
Convulsions	0.06	-0.03, 0.14	0.07	-0.02, 0.16

Very high respiratory rate	0.18	-0.06, 0.41	0.16	-0.07, 0.38
Stridor	0.05	-0.16, 0.26	0.04	-0.17, 0.24
Cyanosis	0.29	-0.53, 1.10	0.27	-0.57, 1.11
Indrawing	0.22	0.08, 0.36	0.23	0.11, 0.35
Grunting	0.07	-0.21, 0.35	0.07	-0.20, 0.35
Crackles	0.06	-0.03, 0.15	0.06	-0.03, 0.15
Difficulty drinking	-0.12	-0.21, -0.03	-0.12	-0.22, -0.02
Wheeze	0.01	-0.13, 0.15	0.02	-0.12, 0.15
Capillary refill	-0.10	-0.38, 0.19	-0.11	-0.40, 0.19
Pallor	0.06	-0.03, 0.15	0.06	-0.03, 0.16
Stiff neck	-0.04	-0.22, 0.14	-0.03	-0.21, 0.15
Bulging fontanelle	-0.12	-0.42, 0.18	-0.16	-0.45, 0.13
Oedema	-0.05	-0.25, 0.15	-0.05	-0.24, 0.15
Not alert	0.26	0.03, 0.48	0.26	0.05, 0.48
2 days of illness before admission	0.08	-0.01, 0.18	0.09	-0.01, 0.19
3 days	0.08	-0.02, 0.17	0.08	-0.02, 0.18
4 days	0.01	-0.12, 0.14	0.01	-0.11, 0.14
4+ days	0.00	-0.09, 0.09	0.00	-0.09, 0.10
Cyanosis x Not alert	-0.34	-1.26, 0.58	-0.35	-1.22, 0.53
Grunting x Not alert	-0.16	-0.54, 0.22	-0.17	-0.54, 0.20
Difficulty feeding x Not alert	-0.03	-0.32, 0.26	-0.04	-0.30, 0.23
Cyanosis x Grunting	-0.48	-1.27, 0.31	-0.49	-1.28, 0.29
Difficulty feeding x Cyanosis	0.49	-0.24, 1.21	0.55	-0.18, 1.28
Difficulty feeding x Grunting	-0.06	-0.32, 0.19	-0.07	-0.30, 0.16
Cyanosis x Indrawing	-0.29	-1.17, 0.60	-0.37	-1.27, 0.53
Indrawing x Grunting	-0.13	-0.40, 0.13	-0.15	-0.43, 0.13
Difficulty feeding x Indrawing	0.10	-0.07, 0.26	0.10	-0.06, 0.26
Indrawing x Not alert	-0.20	-0.55, 0.15	-0.21	-0.53, 0.11
Very high respiratory rate x Not alert	0.25	-0.22, 0.72	0.21	-0.25, 0.66
Very high respiratory rate x Cyanosis	0.21	-0.85, 1.26	0.38	-0.61, 1.38

Very high respiratory rate x Grunting	-0.04	-0.33, 0.25	0.00	-0.29, 0.29
Difficulty feeding x Very high respiratory rate	0.12	-0.10, 0.34	0.15	-0.09, 0.39
Very high respiratory rate x Indrawing	0.02	-0.27, 0.30	0.02	-0.26, 0.31

[i] The level of pulse oximeter use at the hospital during the month of admission of the child

Research Question 2: Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?

Variable value	10 imputations		30 imputations	
	Coefficient	Confidence interval	Coefficient	Confidence interval
Hospital 2	-1.01	-1.23, -0.79	-1.03	-1.26, -0.81
Hospital 3	-0.77	-1.05, -0.49	-0.76	-1.03, -0.49
Hospital 4	-0.14	-0.33, 0.04	-0.14	-0.33, 0.05
Hospital 5	-0.08	-0.25, 0.10	-0.09	-0.27, 0.09
Hospital 6	-0.37	-0.53, -0.21	-0.38	-0.54, -0.21
Hospital 7	-0.60	-0.82, -0.38	-0.59	-0.81, -0.37
Female	0.07	-0.03, 0.17	0.08	-0.02, 0.18
Age	-0.05	-0.08, -0.03	-0.06	-0.08, -0.03
Weight-for-age	-0.02	-0.05, 0.01	-0.02	-0.05, 0.01
March 2014-Aug 2014	-0.83	-1.28, -0.38	-0.79	-1.16, -0.43
Sept 2014-Feb 2015	-0.71	-1.15, -0.26	-0.67	-1.04, -0.31
March 2015-Aug 2015	-0.65	-1.09, -0.21	-0.61	-0.98, -0.25
Sept 2015-Feb 2016	-0.56	-1.00, -0.12	-0.52	-0.90, -0.15
21-50% pulse oximeter use	-0.35	-0.52, -0.17	-0.34	-0.52, -0.16
51-80% pulse oximeter use	-0.63	-0.81, -0.45	-0.63	-0.81, -0.45
81-100% pulse oximeter use	-0.60	-0.82, -0.38	-0.59	-0.82, -0.37
PAR present not used	0.05	-0.59, 0.69	0.10	-0.42, 0.62
PAR used	0.32	-0.09, 0.73	0.34	-0.06, 0.73
Weekend admission	0.09	-0.02, 0.20	0.09	-0.02, 0.20
Fever	-0.23	-0.35, -0.11	-0.24	-0.36, -0.12
Cough	0.10	-0.04, 0.24	0.09	-0.05, 0.23

Difficulty breathing	0.69	0.55, 0.82	0.69	0.56, 0.82
Vomit everything	-0.12	-0.27, 0.03	-0.14	-0.29, 0.02
Difficulty feeding	-0.08	-0.20, 0.03	-0.07	-0.18, 0.04
Convulsions	-0.15	-0.35, 0.04	-0.16	-0.36, 0.04
Very high respiratory rate	0.62	0.47, 0.77	0.63	0.49, 0.76
Pulse oximeter use	0.36	0.23, 0.49	0.35	0.22, 0.48
Stridor	0.20	-0.03, 0.43	0.22	-0.01, 0.45
Cyanosis	0.63	0.25, 1.01	0.65	0.28, 1.01
Indrawing	0.98	0.83, 1.12	0.98	0.84, 1.13
Grunting	0.56	0.44, 0.68	0.56	0.44, 0.69
Crackles	0.17	0.05, 0.28	0.16	0.05, 0.28
Difficulty drinking	0.34	0.19, 0.48	0.33	0.19, 0.47
Wheeze	0.01	-0.16, 0.17	0.01	-0.15, 0.17
Capillary refill	0.02	-0.58, 0.61	0.00	-0.52, 0.53
Pallor	0.36	0.19, 0.53	0.37	0.19, 0.54
Stiff neck	0.00	-0.33, 0.33	0.01	-0.33, 0.35
Bulging fontanelle	-0.04	-0.49, 0.41	-0.06	-0.53, 0.41
Oedema	0.01	-0.34, 0.37	-0.02	-0.37, 0.32
Not alert	0.44	0.24, 0.64	0.43	0.24, 0.63
2 days of illness before admission	-0.11	-0.27, 0.05	-0.10	-0.26, 0.06
3 days	-0.15	-0.31, 0.01	-0.15	-0.31, 0.01
4 days	-0.21	-0.43, 0.01	-0.22	-0.42, -0.01
4+ days	-0.17	-0.33, -0.02	-0.18	-0.33, -0.03
Pneumonia diagnosis	0.57	0.41, 0.73	0.57	0.40, 0.74
Malaria diagnosis	-0.19	-0.40, 0.03	-0.18	-0.38, 0.03
TB diagnosis	-0.12	-0.44, 0.21	-0.06	-0.38, 0.25
Diarrhoea diagnosis	-0.17	-0.31, -0.03	-0.17	-0.30, -0.03
Dehydration diagnosis	-0.04	-0.20, 0.13	-0.04	-0.20, 0.13
Malnutrition diagnosis	-0.26	-0.45, -0.07	-0.27	-0.46, -0.08
Anaemia diagnosis	0.23	0.00, 0.46	0.24	0.01, 0.48

Meningitis diagnosis	0.19	-0.05, 0.44	0.20	-0.05, 0.45
Asthma diagnosis	0.65	0.43, 0.87	0.65	0.44, 0.87
Bronchiolitis diagnosis	0.63	0.38, 0.88	0.63	0.38, 0.88
Sepsis diagnosis	0.46	0.10, 0.82	0.45	0.08, 0.81
Antimalarials: neither	0.27	0.03, 0.51	0.28	0.07, 0.50
Antimalarials: oral	-0.11	-0.56, 0.34	-0.11	-0.57, 0.34

Research Question 3: Are pulse oximeter readings below 90% associated with the prescription of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?

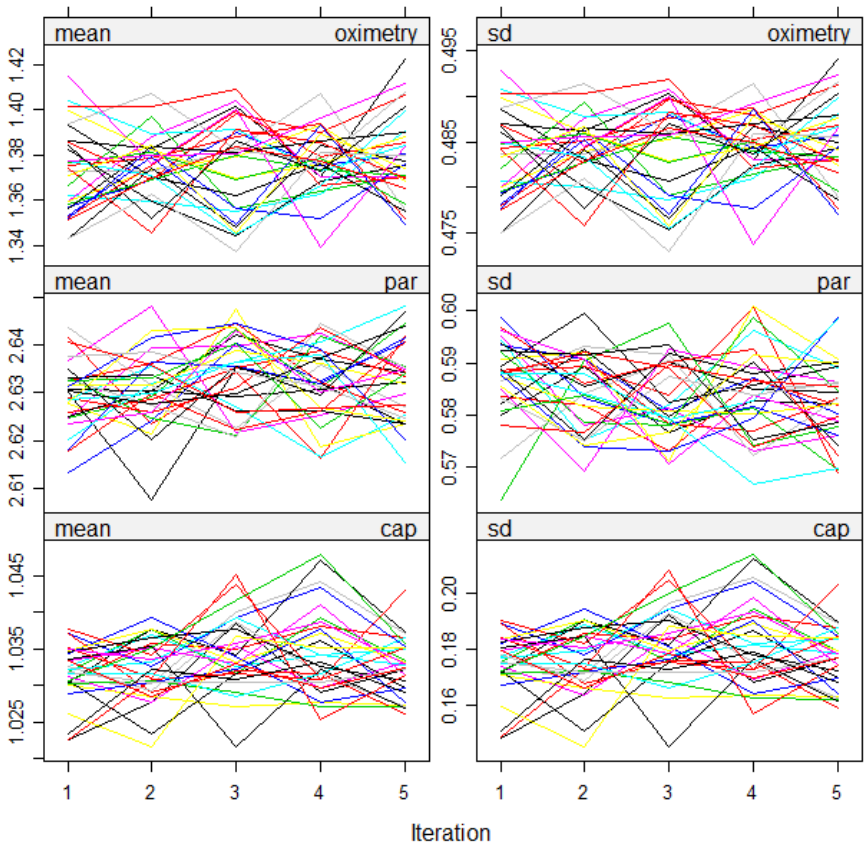
Variable value	**10 imputations**		**30 imputations**	
	Coefficient	**Confidence interval**	**Coefficient**	**Confidence interval**
Hospital 2	-0.50	-0.90, -0.11	-0.51	-0.90, -0.11
Hospital 3	-1.59	-2.07, -1.11	-1.60	-2.08, -1.12
Hospital 4	-0.22	-0.50, 0.05	-0.23	-0.51, 0.04
Hospital 5	-0.11	-0.34, 0.12	-0.11	-0.34, 0.12
Hospital 6	-0.37	-0.59, -0.14	-0.38	-0.60, -0.15
Hospital 7	-0.64	-0.90, -0.37	-0.64	-0.91, -0.37
Female	0.05	-0.09, 0.18	0.04	-0.09, 0.18
Age	-0.03	-0.07, 0.00	-0.03	-0.07, 0.00
Weight-for-age	-0.01	-0.05, 0.02	-0.01	-0.05, 0.02
March 2014-Aug 2014	-0.83	-1.51, -0.15	-0.86	-1.55, -0.18
Sept 2014-Feb 2015	-0.77	-1.44, -0.09	-0.80	-1.48, -0.12
March 2015-Aug 2015	-0.82	-1.49, -0.15	-0.85	-1.53, -0.18
Sept 2015-Feb 2016	-0.75	-1.42, -0.07	-0.78	-1.46, -0.10
21-50% pulse oximeter use	-0.67	-1.04, -0.30	-0.67	-1.04, -0.30
51-80% pulse oximeter use	-0.76	-1.12, -0.41	-0.76	-1.12, -0.41
81-100% pulse oximeter use	-0.72	-1.10, -0.34	-0.72	-1.10, -0.34
PAR present not used	0.14	-0.69, 0.98	0.07	-0.80, 0.93

PAR used	0.39	-0.19, 0.98	0.35	-0.26, 0.97
Fever	-0.12	-0.28, 0.04	-0.12	-0.28, 0.04
Difficulty breathing	0.56	0.40, 0.73	0.57	0.41, 0.74
Vomit everything	-0.21	-0.41, 0.00	-0.21	-0.41, 0.00
Very high respiratory rate	0.44	0.27, 0.62	0.45	0.28, 0.63
Pulse oximeter use	1.19	1.04, 1.34	1.19	1.03, 1.34
Cyanosis	0.55	0.03, 1.06	0.55	0.05, 1.05
Indrawing	0.88	0.70, 1.06	0.87	0.69, 1.06
Grunting	0.51	0.35, 0.67	0.51	0.35, 0.67
Crackles	0.31	0.16, 0.46	0.31	0.16, 0.45
Difficulty drinking	0.31	0.13, 0.49	0.31	0.13, 0.50
Pallor	0.25	0.02, 0.47	0.24	0.02, 0.47
Not alert	0.38	0.13, 0.64	0.38	0.12, 0.63
2 days of illness before admission	-0.12	-0.33, 0.10	-0.11	-0.32, 0.11
3 days	-0.07	-0.28, 0.14	-0.06	-0.28, 0.15
4 days	-0.17	-0.45, 0.10	-0.18	-0.45, 0.09
4+ days	-0.11	-0.31, 0.09	-0.10	-0.30, 0.10
Pneumonia diagnosis	0.53	0.31, 0.75	0.53	0.31, 0.74
Malaria diagnosis	-0.15	-0.44, 0.14	-0.15	-0.44, 0.14
TB diagnosis	-0.32	-0.76, 0.12	-0.32	-0.76, 0.12
Diarrhoea diagnosis	-0.14	-0.32, 0.04	-0.14	-0.32, 0.04
Dehydration diagnosis	-0.03	-0.25, 0.20	-0.03	-0.25, 0.20
Malnutrition diagnosis	-0.28	-0.52, -0.03	-0.27	-0.52, -0.03
Anaemia diagnosis	0.01	-0.31, 0.33	0.02	-0.30, 0.34
Meningitis diagnosis	0.17	-0.08, 0.41	0.17	-0.08, 0.41
Asthma diagnosis	0.45	0.19, 0.72	0.45	0.19, 0.72
Bronchiolitis diagnosis	0.55	0.20, 0.89	0.55	0.20, 0.89
Sepsis diagnosis	0.33	-0.13, 0.80	0.33	-0.13, 0.79
Antimalarials: neither	0.23	-0.07, 0.54	0.23	-0.07, 0.53
Antimalarials: oral	-0.09	-0.79, 0.60	-0.09	-0.79, 0.60

Appendix 5.7: mean and standard deviation for variables across the iterations of the 30 imputations

The mean and standard deviation for each variable across the iterations of the 30 imputations was plotted. These displayed intermingling streams without definite trends, indicating convergence had been achieved.[van Buuren&Groothuis-Oudshoorn,2011] A selection of examples of this are shown below: the figures for the outcome of interest (pulse oximeter use – "oximetry") and the two variables with the largest amount of missing data (Paediatric Admissions Record use – "par", and capillary refill – "cap"), for Research Question 1.

Research Question 1: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?



Note: the Y-axis scales are in small increments and show little difference in results

Appendix 5.8: Checking for bias in the imputed data due to violation of the MAR assumption

Based on the following analyses, we can conclude that the multiple imputation process accurately retained the existing data's characteristics in estimating the missing values:

i) Comparison of original data vs. imputed data

The means and variances of the continuous variables *Age* and *Weight-for-age*, and the proportions of *PAR use*, *Very high respiratory rate*, and *Capillary refill* (the 3 categorical variables with the largest amount of missing data) were essentially constant across each of Research Question 1's 30 imputed datasets. Box plots and density plots of *Age* and *Weight-for-age* values show close similarities between the original dataset and the imputed datasets for each Research Question. (See Figures A5.8.1 and A5.8.2).

ii) Comparison of complete case data from the original dataset vs. imputed data

The imputed data summary statistics differed from the complete case summary statistics for *Admission time period*, *PAR use* and *Pulse oximeter use*, but were similar to those of the original dataset, which is to be expected because the children with missing data also differed from the complete case children for these variables (see Appendix 5.4) and the imputation process aims to maintain the original dataset's characteristics. The imputed data summary statistics were similar to the complete case summary statistics for all other variables. Although there are therefore some differences between the complete case data and imputed data, given that this is a comparison of 10,000 vs. 800,000 measurements, across 45 variables, it is remarkable how little variation there is.

Finally, there were some differences between the coefficients and confidence intervals produced when using complete cases vs. the imputed datasets. Some differences were to be expected, given that the imputation process maintains the original dataset's characteristics (and the characteristics of the original dataset's complete cases differed from the characteristics of the overall original dataset, because of differences between children with vs. without missing data – see Appendix 5.4). However, these differences were not substantial enough to warrant concern as each confidence interval of the complete cases overlapped with the corresponding imputed data's confidence interval.

Figure A5.8.1: Box plots displaying the mean, interquartile range, and distribution of the data for the original dataset (shown in blue) and for imputed dataset 1 through 30 (shown in red), for the two continuous variables (age in years and weight for age)

Figure A5.8.1a: Research Question 1: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

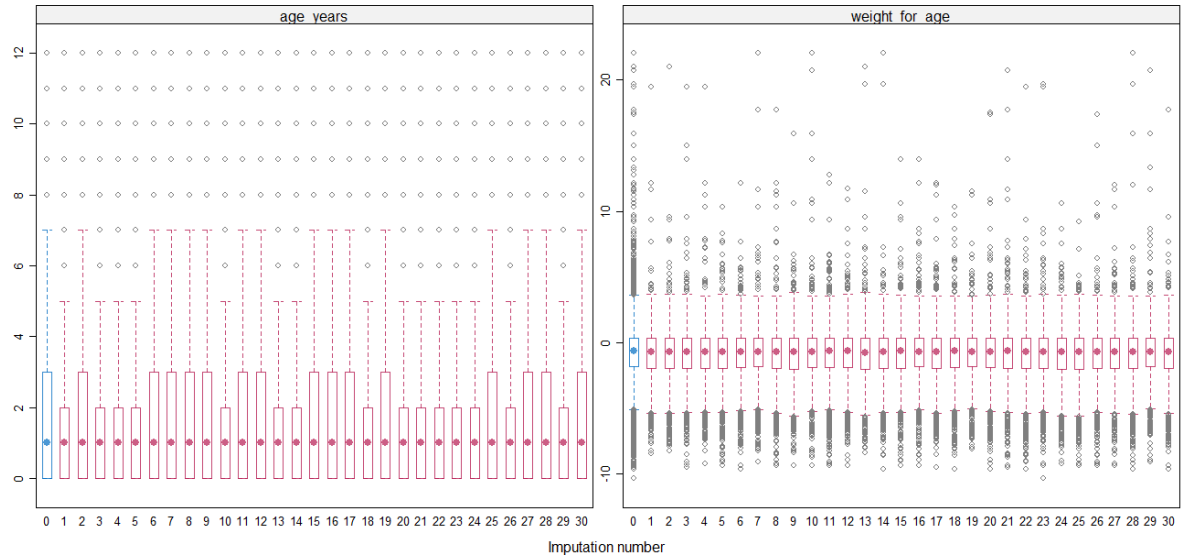


Figure A5.8.1b: Research Question 2: Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?

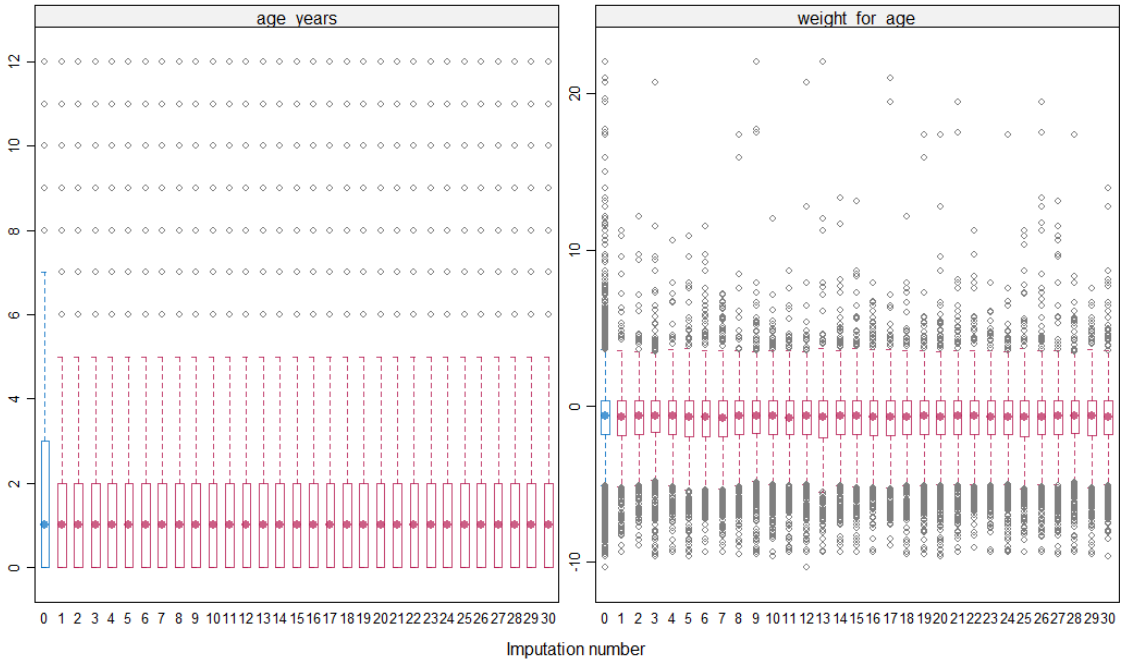
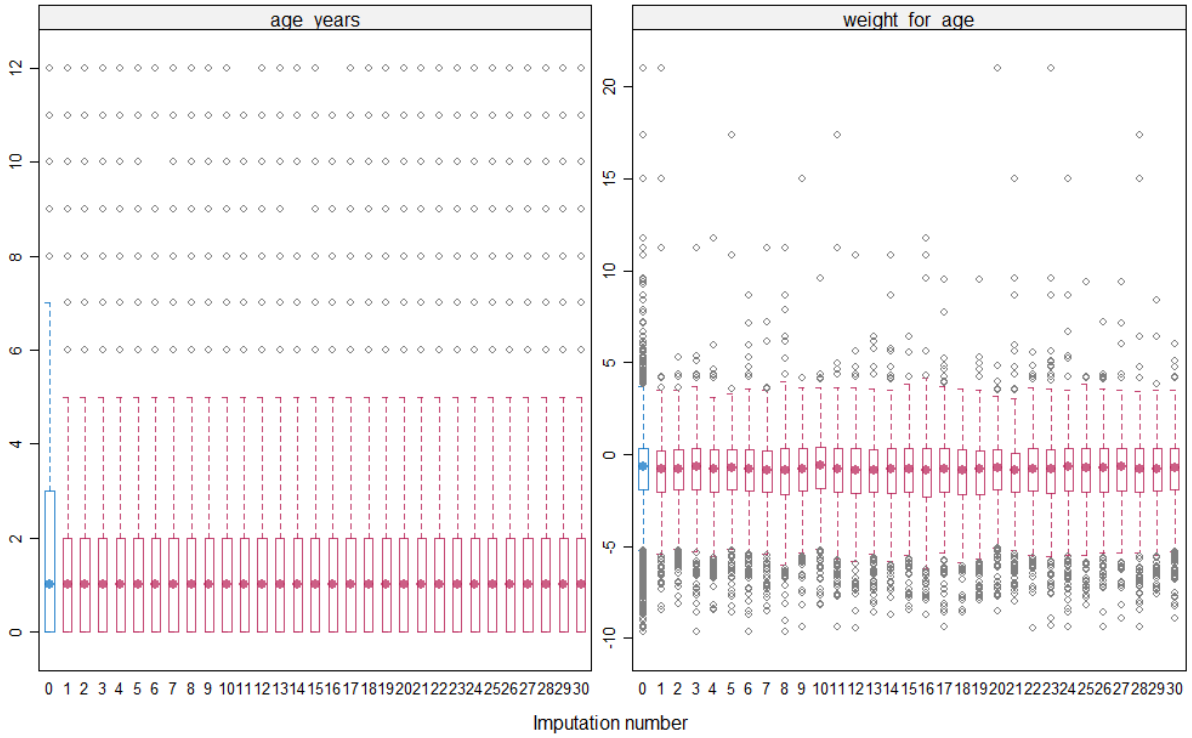


Figure A5.8.1c: Research Question 3: Are pulse oximeter readings below 90% associated with the delivery of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?



We can therefore see that, for each Research Question, the mean and distribution of the data for age in years and weight for age do not differ much between the original dataset and each imputed dataset.

Figure A5.8.2: Density plots of continuous variable values across imputations [note: blue=original data, red=imputed data]

Figure A5.8.2a: Research Question 1 dataset: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

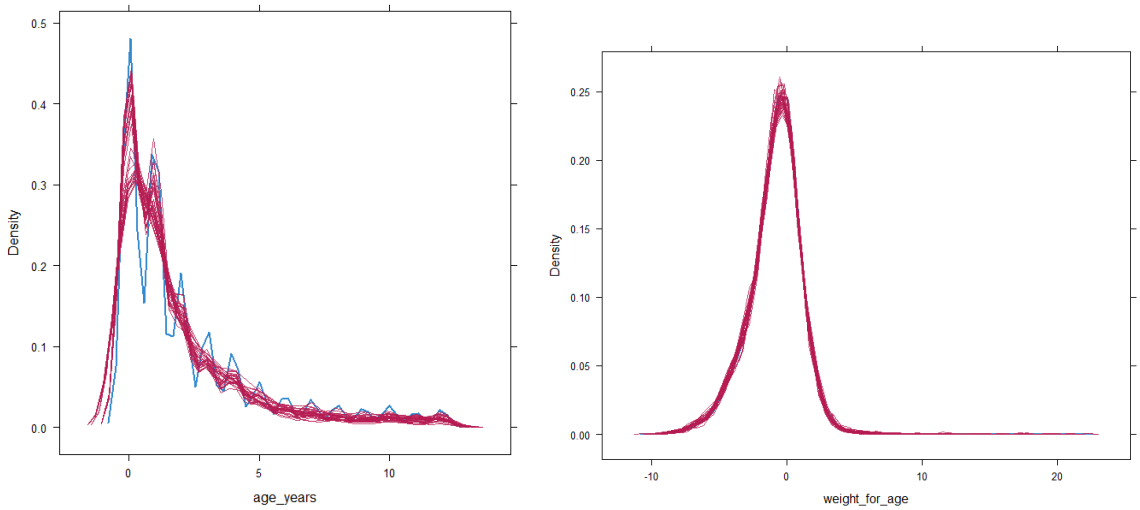


Figure A5.8.2b: Research Question 2: Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?

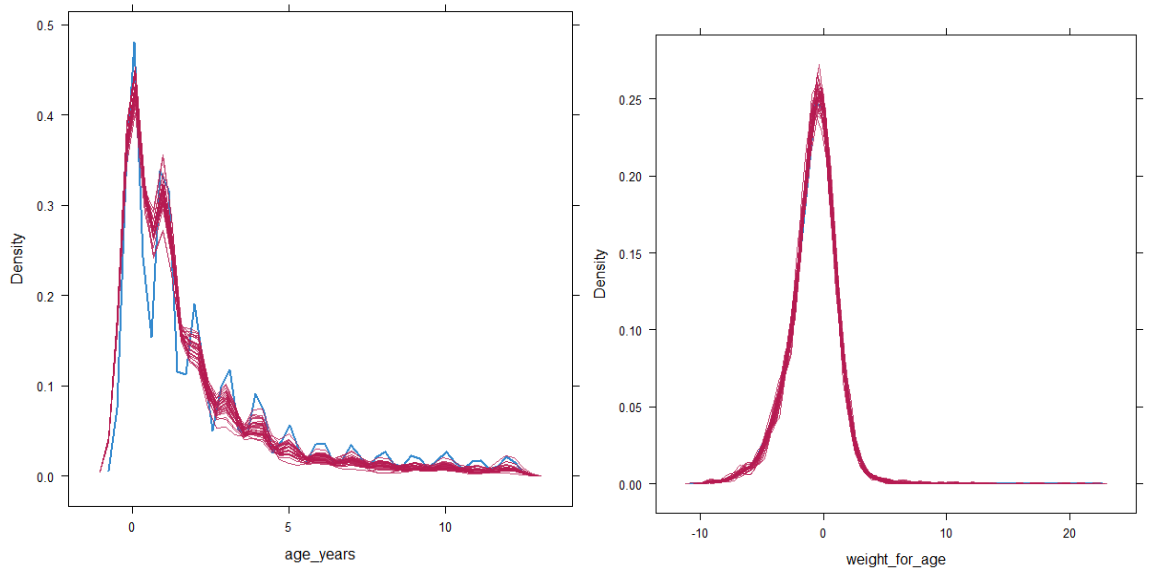
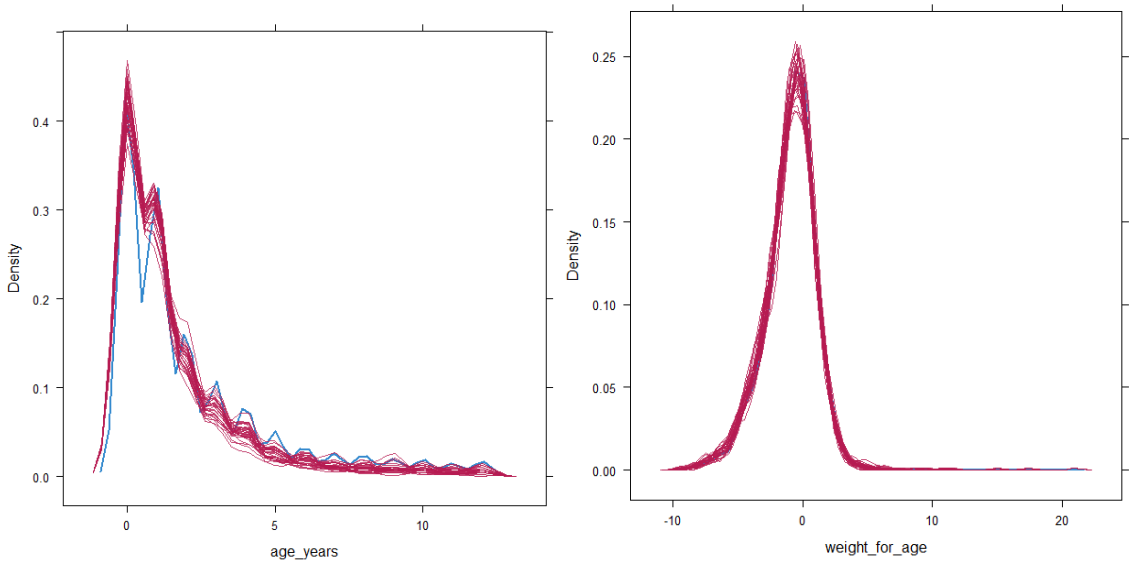


Figure A5.8.2c: Research Question 3: Are pulse oximeter readings below 90% associated with the delivery of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?



Appendix 5.9: multicollinearity analyses

Research Question 1: Which population of children who attend a Kenyan hospital are most likely to receive a pulse oximeter reading?

As discussed in Section 3.11.7, when a Generalized Variable Inflation Factor (GVIF) value of >2.5 was found, I further assessed this variable's potential multicollinearity by exploring its relationship with other variables with which it may have a multicollinear relationship.

The variables that had GVIF values above the 2.5 threshold were:

- *Hospital* – GVIF: 2.7

This high value was probably due to the powerful influence of context in that many clinical factors would have differed by hospital, because of the differences in clinical practices, norms, guidelines, equipment and patient make-up across hospitals.

- *Admission time period* – GVIF: 5.2

This high value was probably because care is likely to have changed over time, potentially as a result of higher level organisational factors such as feedback from CIN reports [see Section 3.3.3 and 7.2]

- *PAR use* – GVIF: 3.91

This high value was probably because PAR presence/use is probably highly related to hospital because in some hospitals it is a policy to use the PAR and so it will be widely used, whereas in others less emphasis is placed on the form.

I decided to keep all of these variables in the regression models because the reasons for why multicollinearity is suggested for these variables is fairly clear, and because it has been argued in the literature that variables with potential multicollinearity can be kept in the model if they are control variables [Allison,2012], which these all are.

Research Question 2: Are children who obtain pulse oximeter readings more likely to obtain oxygen therapy than children with similar characteristics who do not obtain pulse oximeter readings?

Similarly to Research Question 1, *Hospital*, *Admission time period* and *PAR use* all had GVIF values above the 2.5 threshold when the Research Question 2 full model was tested for multicollinearity (GVIF=4.4, 6.6, 4.6, respectively), probably for the same reasons as those outlined for Research Question 1. In addition, the variable of *Pulse oximeter use at hospital during month of admission* had a GVIF of 3.4. This high value was probably because of this variable's relation with hospital, which was used to help create it. I decided to keep all of these variables in the model, for the same reasons as those given for Research Question 1.

Research Question 3: Are pulse oximeter readings below 90% associated with the delivery of oxygen therapy compared with readings of 90% or higher, in children being treated at a Kenyan hospital?

Similarly to Research Question 1 and 2, *Hospital*, *Admission time period*, and *PAR use* all had GVIF values above the 2.5 threshold when the Research Question 3 full model was tested for multicollinearity (GVIF=4.0, 15.3, 10.5 respectively), probably for the same reasons as those outlined for Research Question 1. I decided to keep all of these variables in the model, for the same reasons as those given for Research Question 1.

Appendix 5.10: Odds ratios and confidence intervals produced from Research Question 1

Variable	Baseline	Odds ratio	Confidence interval
Intercept	n/a	0.02	0.01, 0.02
Hospital 2	Hospital 1	0.82	0.70, 0.95
Hospital 3		1.39	1.22, 1.57
Hospital 4		0.97	0.88, 1.07
Hospital 5		1.16	1.04, 1.30
Hospital 6		0.95	0.85, 1.06
Hospital 7		1.29	1.13, 1.47
Female	Male	0.99	0.93, 1.05
Age	n/a	0.98	0.97, 0.99
Weight-for-age	n/a	1.01	0.99, 1.02
March 2014-Aug 2014	Sept 2013 – Feb 2014	1.22	0.98, 1.52
Sept 2014-Feb 2015		1.39	1.09, 1.78
March 2015-Aug 2015		1.49	1.18, 1.88
Sept 2015-Feb 2016		1.59	1.26, 2.02
21-50% pulse oximeter use[i]	0-20% pulse oximeter use	10.49	9.09, 12.09
51-80% pulse oximeter use[i]		30.38	26.16, 35.28
81-100% pulse oximeter use[i]		101.40	85.79, 119.85
PAR present not used	PAR not present	2.93	2.05, 4.19
PAR used		2.41	1.98, 2.94
Weekend admission	Weekday admission	0.91	0.85, 0.98
Fever	No fever	1.12	1.04, 1.20
Cough	No cough	1.12	1.04, 1.21
Difficulty breathing	No difficulty breathing	1.13	1.05, 1.22
Vomit everything	Not vomiting everything	0.84	0.78, 0.91
Very high respiratory rate	Low/normal respiratory rate	1.27	1.13, 1.43
Indrawing	No indrawing	1.28	1.17, 1.40
Difficulty drinking	No difficulty drinking	0.89	0.80, 0.98
Lack of alertness	Alert	1.30	1.09, 1.55
Indrawing x Lack of alertness	n/a	0.75	0.57, 0.98

[i] The level of pulse oximeter use at the hospital during the month of admission of the child

Appendix 5.11: odds ratios and confidence intervals produced when the best model for Research Question 1 is run separately with each hospital

Variable	Hospital 1		Hospital 2		Hospital 3		Hospital 4		Hospital 5		Hospital 6		Hospital 7	
	Odds ratio	Conf. interval	Odds ratio	Conf. interval	Odds ratio	Conf. interval	Odds ratio	Conf. interval	Odds ratio	Conf. interval	Odds ratio	Conf. interval	Odds ratio	Conf. interval
Sex	0.90	0.78, 1.04	1.03	0.77, 1.36	0.91	0.75, 1.11	1.00	0.89, 1.13	1.00	0.85, 1.18	1.03	0.88, 1.20	1.16	0.95, 1.40
Age in years	0.99	0.96, 1.02	1.02	0.95, 1.09	0.99	0.95, 1.02	0.98	0.96, 1.00	0.96	0.93, 1.00	0.96	0.93, 0.99	1.01	0.97, 1.05
Weight-for-age	1.00	0.96, 1.04	1.00	0.93, 1.08	1.04	0.98, 1.10	1.02	0.98, 1.06	0.99	0.95, 1.03	0.98	0.95, 1.02	1.01	0.97, 1.06
March 2014-Aug 2014	0.73	0.31, 1.74	1.39E+5	0.00, n/a	1.0E+6	0.00, 8.2E+239	1.22	0.84, 1.77	1.12	0.72, 1.74	1.00	0.59, 1.69	1.05	0.43, 2.56
Sept 2014-Feb 2015	0.65	0.26, 1.64	2.64E+4	0.00, n/a	2.08E+6	0.00, 1.7E+240	0.88	0.57, 1.35	1.09	0.66, 1.80	1.51	0.86, 2.63	0.97	0.37, 2.56
March 2015-Aug 2015	0.99	0.40, 2.44	1.41E+6	0.00, n/a	1.39E+6	0.00, 1.1E+240	1.62	1.12, 2.33	1.05	0.67, 1.64	1.78	0.99, 3.19	1.04	0.40, 2.70
Sept 2015-Feb 2016	0.96	0.38, 2.39	1.67E+6	0.00, n/a	1.85E+6	0.00, 1.5E+240	1.48	1.02, 2.15	1.34	0.85, 2.11	1.61	0.91, 2.83	1.05	0.41, 2.71
21-50% oximeter use	6.74	4.46, 10.18	6.55	3.99, 10.75	28.34	16.85, 47.68	8.97	6.85, 11.74			5.31	4.08, 6.92	2.14	1.28, 3.58
51-80% oximeter use	18.79	11.35, 31.10	27.98	14.84, 52.76	78.39	45.34, 135.53	17.18	12.79, 23.07	3.05	2.35, 3.95	12.04	8.96, 16.19	11.55	6.74, 19.80
81-100% oximeter use	84.76	45.27, 158.71	53.77	24.98, 115.73	207.19	115.22, 372.57			9.14	6.93, 12.04	35.71	22.73, 56.11	42.02	23.48, 75.20
PAR present not used	7.90	1.37, 45.55	0.00	0.00, n/a	0.00	0.00, n/a	2.60	1.53, 4.42			1.19	0.61, 2.33	1.69	0.24, 11.95
PAR used	19.59	7.77, 49.41	2.42	1.22, 4.82	3.17	2.41, 4.16	1.67	1.21, 2.31	0.94	0.62, 1.41	1.15	0.78, 1.69	2.51	0.79, 7.99
Weekend admission	0.93	0.80, 1.09	1.71	1.24, 2.35	0.83	0.66, 1.04	0.86	0.75, 0.99	1.01	0.84, 1.21	0.75	0.62, 0.91	0.99	0.80, 1.23
Fever	1.05	0.89, 1.23	0.97	0.72, 1.32	1.11	0.83, 1.48	1.29	1.11, 1.49	1.17	0.96, 1.43	1.07	0.89, 1.30	1.01	0.82, 1.24
Cough	1.02	0.87, 1.21	1.90	1.35, 2.68	1.14	0.91, 1.43	1.13	0.98, 1.29	1.02	0.85, 1.24	1.11	0.92, 1.34	1.20	0.97, 1.49
Difficulty breathing	1.18	0.99, 1.41	1.39	0.98, 1.95	1.03	0.75, 1.41	1.10	0.94, 1.30	1.02	0.84, 1.24	1.27	1.04, 1.56	1.09	0.85, 1.39
Vomit everything	0.97	0.81, 1.17	0.85	0.59, 1.22	0.86	0.67, 1.11	0.78	0.67, 0.91	0.87	0.71, 1.06	0.82	0.68, 1.00	0.95	0.72, 1.26
Very high respiratory rate	1.13	0.89, 1.43	1.14	0.68, 1.92	1.22	0.71, 2.13	1.39	1.10, 1.74	1.02	0.70, 1.48	1.64	1.24, 2.15	1.39	0.95, 2.04

Indrawing	1.34	1.11, 1.60	0.80	0.57, 1.14	1.02	0.69, 1.50	1.02	0.85, 1.23	1.78	1.43, 2.21	1.29	1.05, 1.59	1.68	1.24, 2.28
Difficulty drinking	0.88	0.70, 1.11	0.93	0.56, 1.55	0.81	0.60, 1.12	0.97	0.79, 1.19	0.95	0.76, 1.19	0.93	0.77, 1.13	0.63	0.45, 0.88
Lack of alertness	1.05	0.64, 1.73	2.74	0.84, 9.01	1.43	0.83, 2.46	1.43	1.06, 1.92	1.41	0.90, 2.21	1.12	0.77, 1.65	1.46	0.66, 3.21
Indrawing x Lack of alertness	0.75	0.38, 1.48	0.76	0.15, 3.96	1.08	0.39, 3.03	0.93	0.55, 1.57	0.51	0.28, 0.94	0.99	0.55, 1.77	0.42	0.13, 1.32

Variables shaded in green are those found to be statistically significant when data from all hospitals were analysed together

Odds ratios shaded in blue are those which differ from the values produced when data from all hospitals were analysed together, in terms of whether they are statistically significant (based on confidence intervals not crossing 1)

Appendix 5.12: Odds ratios and confidence intervals produced from the Research Question 1 pneumonia analyses

Variable	Baseline	Children with pneumonia		Children without pneumonia	
		Odds ratio	Confidence interval	Odds ratio	Confidence interval
Hospital 2	Hospital 1	**0.70**	0.56, 0.87	0.97	0.78, 1.20
Hospital 3		**1.30**	1.04, 1.61	**1.40**	1.20, 1.64
Hospital 4		0.95	0.83, 1.10	0.97	0.84, 1.11
Hospital 5		**1.28**	1.09, 1.49	1.06	0.90, 1.26
Hospital 6		1.15	1.00, 1.33	**0.78**	0.67, 0.92
Hospital 7		**1.39**	1.15, 1.68	**1.21**	1.01, 1.44
Female	Male	0.95	0.87, 1.04	1.03	0.95, 1.12
Age	n/a	1.00	0.98, 1.02	**0.98**	0.97, 1.00
Weight-for-age	n/a	1.02	1.00, 1.05	0.99	0.97, 1.01
March 2014-Aug 2014	Sept 2013 – Feb 2014	1.02	0.73, 1.42	**1.42**	1.06, 1.91
Sept 2014-Feb 2015		1.04	0.74, 1.48	**1.69**	1.22, 2.34
March 2015-Aug 2015		1.35	0.96, 1.90	**1.62**	1.18, 2.21
Sept 2015-Feb 2016		**1.42**	1.01, 2.02	**1.73**	1.26, 2.37
21-50% pulse oximeter use	0-20% pulse oximeter use	**9.15**	7.53, 11.11	**11.88**	9.74, 14.49
51-80% pulse oximeter use		**25.00**	20.40, 30.63	**36.32**	29.71, 44.39
81-100% pulse oximeter use		**90.54**	70.98, 115.48	**116.06**	92.50, 145.63
PAR present not used	PAR not present	**2.03**	1.24, 3.30	**3.51**	2.19, 5.63
PAR used		**1.91**	1.41, 2.57	**2.69**	2.13, 3.41
Weekend admission	Weekday admission	**0.87**	0.79, 0.97		
Fever	No fever			**1.15**	1.05, 1.26
Cough	No cough			**1.10**	1.01, 1.21
Vomit everything	Not vomiting everything			**0.82**	0.74, 0.90
Very high respiratory rate	Low / normal respiratory rate	**1.24**	1.09, 1.41	**1.30**	1.00, 1.68
Cyanosis	No cyanosis	**3.75**	1.24, 11.41		

Indrawing	No indrawing	**1.23**	1.11, 1.37		
Difficulty drinking	No difficulty drinking	**0.83**	0.73, 0.95		
Wheeze	Not wheezing			**1.48**	1.10, 1.99
Not alert	Alert	**1.62**	1.08, 2.43	**1.25**	1.06, 1.48
Cyanosis x indrawing	n/a	**0.24**	0.07, 0.79		
Indrawing x Not alert	n/a	**0.56**	0.35, 0.89		

Odds ratios in bold are statistically significant, based on confidence intervals not crossing 1; blank values are for variables that were not found in the final 'best' model

Appendix 5.13: Odds ratios and confidence intervals produced from Research Question 2

Variable	Baseline	Odds ratio	Confidence interval
Intercept	n/a	0.04	0.02, 0.07
Pulse oximeter use	No pulse oximeter used	1.42	1.25, 1.62
Hospital 2	Hospital 1	0.36	0.29, 0.45
Hospital 3		0.47	0.36, 0.61
Hospital 4		0.87	0.72, 1.06
Hospital 5		0.91	0.76, 1.09
Hospital 6		0.69	0.59, 0.82
Hospital 7		0.55	0.45, 0.69
Female	Male	1.09	0.98, 1.20
Age years	n/a	0.95	0.92, 0.97
Weight-for-age	n/a	0.98	0.95, 1.01
March 2014-Aug 2014	Sept 2013 – Feb 2014	0.46	0.32, 0.65
Sept 2014-Feb 2015		0.51	0.35, 0.74
March 2015-Aug 2015		0.55	0.38, 0.79
Sept 2015-Feb 2016		0.60	0.41, 0.87
21-50% pulse oximeter use	0-20% pulse oximeter use	0.71	0.60, 0.85
51-80% pulse oximeter use		0.53	0.45, 0.64
81-100% pulse oximeter use		0.55	0.44, 0.69
PAR present not used	PAR not present	1.08	0.65, 1.82
PAR used		1.36	0.91, 2.03
Weekend admission	Weekday admission	1.09	0.98, 1.22
Fever	No fever	0.79	0.70, 0.89
Cough	No cough	1.09	0.95, 1.26
Difficulty breathing	No difficulty breathing	2.00	1.76, 2.28
Vomit everything	Not vomiting everything	0.87	0.75, 1.01
Difficulty feeding	No difficulty feeding	0.93	0.83, 1.04
Convulsions	No convulsions	0.85	0.70, 1.04
Very high respiratory rate	Low/normal respiratory rate	1.87	1.64, 2.14
Cyanosis	No cyanosis	1.92	1.34, 2.76
Indrawing	No indrawing	2.68	2.33, 3.09
Grunting	No grunting	1.77	1.57, 2.00
Crackles	No crackles	1.18	1.06, 1.32
Difficulty drinking	No difficulty drinking	1.39	1.21, 1.59
Pallor	No pallor	1.44	1.22, 1.70
Lack of alertness	Alert	1.55	1.28, 1.87
2 days illness before admission		0.90	0.77, 1.06

3 days illness before admission	1 day illness before admission	0.85	0.73, 1.00
4 days illness before admission		0.80	0.65, 0.98
4+ days illness before admission		0.83	0.72, 0.97
Pneumonia	No pneumonia	1.76	1.49, 2.07
Malaria	No malaria	0.83	0.68, 1.02
TB	No TB	0.94	0.69, 1.30
Diarrhoea	No diarrhoea	0.85	0.74, 0.97
Dehydration	No dehydration	0.97	0.82, 1.14
Malnutrition	No malnutrition	0.77	0.64, 0.92
Anaemia	No anaemia	1.27	1.01, 1.59
Meningitis	No meningitis	1.22	0.98, 1.52
Asthma	No asthma	1.94	1.59, 2.35
Bronchiolitis	No bronchiolitis	1.88	1.47, 2.41
Sepsis	No sepsis	1.56	1.09, 2.24
Antimalarials - neither	Antimalarials - injectable	1.33	1.07, 1.64
Antimalarials - oral		0.89	0.56, 1.39

Appendix 5.14: Odds ratios and confidence intervals produced from the Research Question 2 pneumonia analyses

Variable	Baseline	Children with pneumonia		Children without pneumonia	
		Odds ratio	Confidence interval	Odds ratio	Confidence interval
Hospital 2	Hospital 1	**0.33**	0.25, 0.42	**0.45**	0.27, 0.75
Hospital 3		**0.49**	0.36, 0.66	**0.43**	0.25, 0.75
Hospital 4		0.91	0.74, 1.12	**0.62**	0.39, 0.98
Hospital 5		0.86	0.71, 1.05	1.12	0.71, 1.75
Hospital 6		**0.68**	0.57, 0.81	0.79	0.51, 1.21
Hospital 7		**0.61**	0.48, 0.77	**0.30**	0.17, 0.54
Female	Male	1.11	0.99, 1.24	1.00	0.78, 1.27
Age	n/a	**0.95**	0.92, 0.98	**0.94**	0.90, 0.99
Weight-for-age	n/a	0.99	0.96, 1.02	0.94	0.88, 1.01
March 2014-Aug 2014	Sept 2013 – Feb 2014	**0.45**	0.29, 0.68	**0.49**	0.25, 0.97
Sept 2014-Feb 2015		**0.49**	0.32, 0.76	0.53	0.26, 1.05
March 2015-Aug 2015		**0.56**	0.36, 0.86	**0.43**	0.21, 0.88
Sept 2015-Feb 2016		**0.61**	0.39, 0.94	0.52	0.25, 1.06
21-50% pulse oximeter use[i]	0-20% pulse oximeter use	**0.72**	0.60, 0.88	**0.65**	0.43, 0.98
51-80% pulse oximeter use[i]		**0.54**	0.44, 0.66	**0.53**	0.35, 0.79
81-100% pulse oximeter use[i]		**0.56**	0.44, 0.72	**0.53**	0.32, 0.89
PAR present not used	PAR not present	1.17	0.64, 2.14	0.77	0.28, 2.12
PAR used		1.43	0.93, 2.19	1.25	0.60, 2.60
Weekend admission	Weekday admission	1.11	0.98, 1.25	1.07	0.81, 1.40
Fever	No fever	**0.80**	0.70, 0.92	**0.74**	0.56, 0.97
Cough	No cough	0.99	0.84, 1.16	1.08	0.81, 1.44
Difficulty breathing	No difficulty breathing	**1.80**	1.57, 2.07	**2.52**	1.88, 3.39
Vomit everything	Not vomiting everything	0.87	0.74, 1.03	0.96	0.67, 1.38
Difficulty feeding	No difficulty feeding	0.94	0.83, 1.06	0.94	0.70, 1.27

Convulsions	No convulsions	0.87	0.69, 1.10	0.81	0.56, 1.18
Very high respiratory rate	Low/normal respiratory rate	**1.79**	1.55, 2.07	**2.54**	1.71, 3.76
Pulse oximeter use	Pulse oximeter not used	**1.39**	1.21, 1.61	**1.41**	1.04, 1.90
Cyanosis	No cyanosis	**1.87**	1.26, 2.79	**2.55**	1.06, 6.11
Indrawing	No indrawing	**2.38**	2.04, 2.77	**2.74**	1.96, 3.82
Grunting	No grunting	**1.86**	1.64, 2.12	1.37	0.89, 2.11
Crackles	No crackles	**1.15**	1.02, 1.29	**1.67**	1.17, 2.40
Difficulty drinking	No difficulty drinking	**1.35**	1.16, 1.57	**1.56**	1.12, 2.16
Pallor	No pallor	**1.46**	1.21, 1.76		
Not alert	Alert	1.14	0.91, 1.43	**3.13**	2.19, 4.49
2 days illness before admission	1 day illness before admission	0.95	0.79, 1.13	0.89	0.63, 1.27
3 days illness before admission		0.92	0.77, 1.10	0.72	0.48, 1.07
4 days illness before admission		0.91	0.73, 1.14	**0.41**	0.22, 0.78
4+ days illness before admission		0.87	0.74, 1.03	0.78	0.55, 1.10
Malaria	No malaria	0.93	0.74, 1.16	**0.61**	0.39, 0.95
TB	No TB	0.89	0.63, 1.26	1.31	0.56, 3.10
Diarrhoea	No diarrhoea	0.90	0.78, 1.04	**0.65**	0.46, 0.91
Dehydration	No dehydration	0.94	0.78, 1.14	1.14	0.78, 1.66
Malnutrition	No malnutrition	**0.81**	0.67, 0.99	0.66	0.40, 1.08
Anaemia	No anaemia	1.30	1.00, 1.70	**1.62**	1.10, 2.41
Meningitis	No meningitis	1.20	0.91, 1.59	1.18	0.80, 1.74
Asthma	No asthma	**1.60**	1.29, 2.00	**3.84**	2.42, 6.09
Bronchiolitis	No bronchiolitis	**1.57**	1.19, 2.08	**3.40**	1.87, 6.19
Sepsis	No sepsis	1.21	0.72, 2.03	**2.06**	1.20, 3.54
Antimalarials - neither	Antimalarials - injectable	**1.49**	1.17, 1.89	0.87	0.56, 1.36
Antimalarials - oral		0.96	0.58, 1.59	0.82	0.29, 2.32

Odds ratios in bold are statistically significant, based on confidence intervals not crossing 1

Outputs from the research: Publications, presentations, and presented posters based on the work of this thesis

Publications:

- Enoch, A.J., English, M. and Shepperd, S. (2015) Does pulse oximeter use impact health outcomes? A systematic review. *Archives of Disease in Childhood,* 101, pp. 694-700. See paper below.

Presentations:

- Nuffield Department of Population Health (NDPH) Research Symposium; Oxford, UK; 14th January 2015
- To researchers at the Kenyan Medical Research Institute Wellcome Trust Research Programme (KEMRI-KWTRP); Nairobi, Kenya; 13th June 2016
- To KEMRI-KWTRP researchers; Nairobi, Kenya; 24th November 2016
- NDPH Research Student Seminar; Oxford, UK; 23rd January 2017
- Medical Research Council – Doctoral Training Partnerships (MRC-DTP) conference; Oxford, UK; 22nd June 2017
- Prof Grace Irimu presented some of my analyses to the Kenyan Ministry of Health at the National and County Stakeholder Forum on Expanding Access to Oxygen Therapy; Nairobi, Kenya; September 2017

Posters:

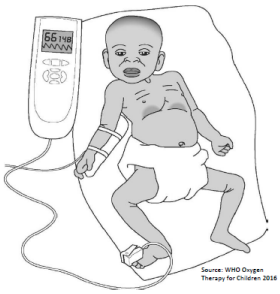
- Crossing Boundaries conference; Oxford, UK; 7th December 2017; see poster below

Pulse oximeter use in low-income settings: a case study of Kenyan hospitals

DPhil thesis of Abigail Enoch; supervisors Prof Mike English and Prof Sasha Shepperd

The problem:

- Pneumonia is the leading cause of death worldwide in children 1 month to 5 years old
- Hypoxemia (low blood oxygen levels) is a common complication of pneumonia
- Pulse oximeters: a low-cost, easy-to-use tool, shown to be effective at detecting hypoxemia
- The World Health Organization recommends using pulse oximeters with all children at admission to hospital
- But oximeters are often not available in low-income settings
- So international efforts have aimed to donate pulse oximeters to these areas
- And yet evidence shows that pulse oximeters are often not used in low-income settings, even when available and yet little research has examined why



Research questions:

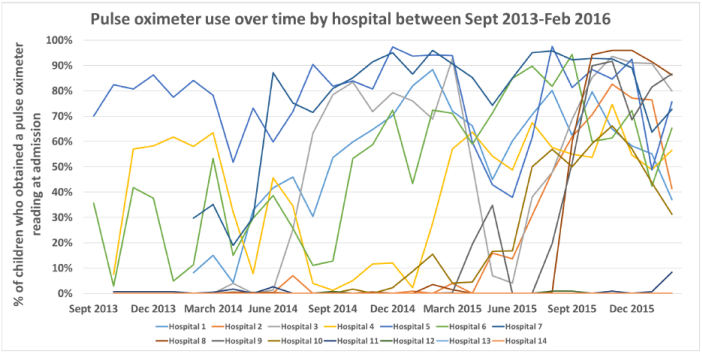
- With which children are pulse oximeters being used?
- Why do healthcare workers (HCWs) choose to use/not use pulse oximeters?
- What are the barriers to pulse oximeter use?

Methods:

- Systematic literature review
- Quantitative analyses of 28,000 children admitted to 7 Kenyan hospitals over 2 ½ years
- Qualitative interviews with 30 hospital staff from 14 Kenyan hospitals

Results:

Large variability in pulse oximeter use within and across Kenyan hospitals over time:

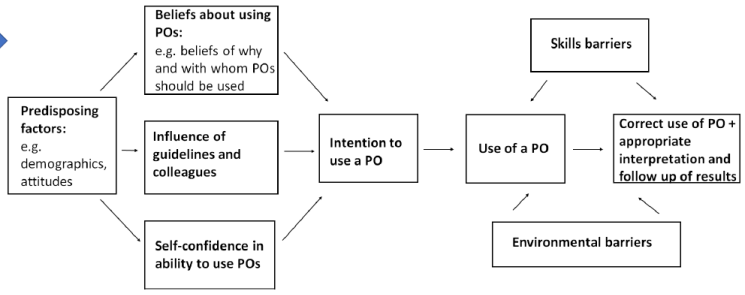


With which children are pulse oximeters being used?

- Those with a high respiratory rate, difficulty breathing, indrawing, not alert
- Those admitted later in study period, to certain hospitals, especially where particular admissions forms are used

Variability within and between hospitals: due to differences in presence of barriers
Increase in use over time: due to uptake of national guidelines and locally-designed form for recording admissions data

What determines whether a pulse oximeter is used appropriately?
Step 1: HCW intention to use
Step 2: HCW ability to use
Step 3: appropriate interpretation



HCWs widely **intended** to use oximeters, at least with a subset of children.
But **barriers** often prevented them:

Skill barriers:
Insufficient formal training on oximeter use meant sometimes HCWs:

- Did not know how to use oximeters correctly
- Mistakenly trusted clinical signs over accurate oximeter results when results contradicted clinical signs

Environmental barriers:

- Inadequate supply of oximeters in the ward, often due to inefficient and unclear procurement processes
- Lack of access to ward's oximeters, due to delays in repairs and battery charging / replacement
- Inappropriately sized oximeters
- Insufficient oxygen availability

Recommendations:

- Increase the supply of oximeters and oxygen
  - Important to consider type of oximeter (e.g. accuracy, power source)
- Improve procurement and repair processes
- Provide more training
  - On how and why to use and interpret
  - Formal training sessions + reminders (e.g. wall charts) + colleague encouragement

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Does pulse oximeter use impact health outcomes? A systematic review

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ABSTRACT

Objective Do newborns, children and adolescents up to 19 years have lower mortality rates, lower morbidity and shorter length of stay in health facilities where pulse oximeters are used to inform diagnosis and treatment (excluding surgical care) compared with health facilities where pulse oximeters are not used?

Design Studies were obtained for this systematic literature review by systematically searching the Database of Abstracts of Reviews of Effects, Cochrane, Medion, PubMed, Web of Science, Embase, Global Health, CINAHL, WHO Global Health Library, international health organisation and NGO websites, and study references.

Patients Children 0–19 years presenting for the first time to hospitals, emergency departments or primary care facilities.

Interventions Included studies compared outcomes where pulse oximeters were used for diagnosis and/or management, with outcomes where pulse oximeters were not used. Main outcome measures: mortality, morbidity, length of stay, and treatment and management changes.

Results The evidence is low quality and hypoxaemia definitions varied across studies, but the evidence suggests pulse oximeter use with children can reduce mortality rates (when combined with improved oxygen administration) and length of emergency department stay, increase admission of children with previously unrecognised hypoxaemia, and change physicians' decisions on illness severity, diagnosis and treatment. Pulse oximeter use generally increased resource utilisation.

Conclusions As international organisations are investing in programmes to increase pulse oximeter use in low-income settings, more research is needed on the optimal use of pulse oximeters (eg, appropriate oxygen saturation thresholds), and how pulse oximeter use affects referral and admission rates, length of stay, resource utilisation and health outcomes.

What is already known on this topic

- Hypoxaemia is a common complication of pneumonia, bronchiolitis, asthma and sepsis and is associated with increased risk of death in children.
- Pulse oximeters are a low-cost intervention that could help reduce child mortality by more effectively diagnosing and monitoring children with hypoxaemia.
- Pulse oximeters are often not available or not used in low-income settings, but several international projects aim to increase their availability and use.

What this study adds

- The evidence, while low quality, suggests pulse oximeter use may improve children's mortality rates, morbidity measurement, hospital length of stay and admission of hypoxic children.
- In the included studies, pulse oximeters were often important for physician's clinical decision-making about children's treatment and management, and their use generally increased resource utilisation.
- More research is needed on optimal thresholds to use for hypoxaemia definitions, and on how pulse oximeter use affects resource utilisation and impacts health outcomes.

INTRODUCTION

In newborns, children and adolescents hypoxaemia is associated with increased risk of death, and is a common complication of bronchiolitis, pneumonia, asthma and other serious conditions (eg, sepsis).[1–4] Pulse oximetry is a low-cost intervention that could reduce child mortality, in line with Millennium Development Goal 4, by enabling early detection of hypoxaemia and improving accurate diagnosis, thereby increasing the chance of prompt, effective treatment.

Despite the potential to improve health outcomes, pulse oximeters are often not available, particularly in low-income settings. For example, only 38% of Nigerian tertiary hospitals and 3 of 22 Kenyan hospitals providing physician internship training had pulse oximeters in 2011 and 2012, respectively.[5 6] To promote access, pulse oximeters have been designed for low-income settings, for example, Lifebox, a low-cost, robust, portable, battery-operated oximeter.[7] Other designs deliver pulse oximeter results to smartphones, using their spread to remote areas.[8] Initiatives supporting pulse oximeter uptake include the WHO's Global Pulse Oximetry Project, Lifebox donations, and the BMJ Christmas Appeal.[7 9 10]

Evidence suggests that pulse oximeters identify 20–30% additional hypoxic children compared with using clinical signs alone, for example, grunting and depressed consciousness, which can be imprecise.[1 11] However, evidence of an association between hypoxaemia and mortality is not necessarily evidence that pulse oximetry implementation improves outcomes, particularly taking a broad health system perspective, when health worker actions, characteristics of children and health

facilities, and additional resources, all interact to impact outcomes.

In the complex world of health systems, pulse oximetry could lead to improved health outcomes and system efficiencies, and reduced resource use, by helping health workers promptly diagnose children and initiate treatment, and by improving diagnostic accuracy, thereby preventing unnecessary admissions and treatments. Alternatively, pulse oximetry could lead to unnecessary admissions, treatment, referrals, and/or discharge delays, if thresholds for admission, referral or intervention are inappropriate.

As pulse oximetry availability increases at primary and community care levels in low-income countries, understanding the health system implications is increasingly important, particularly how pulse oximetry impacts resource utilisation. In high-income countries, guidance for routine screening with pulse oximetry is inconsistent, with some suggesting it is unhelpful.[12–17] Debate also remains about optimum hypoxaemia definitions, especially at altitude.[2 18–22]

We therefore reviewed the evidence on how pulse oximetry introduction impacts health and service use outcomes.

METHODS

We addressed the question "Do newborns, children and adolescents aged up to 19 years have lower mortality rates, lower morbidity, and shorter length of stay where pulse oximeters are used to inform diagnosis and treatment (excluding operative surgical care) compared with where pulse oximeters are not used?" Our secondary research question was, "What proportion of newborns, children and adolescents are given oxygen therapy where pulse oximeters are used compared with where pulse oximeters are not used."

Studies were included if they recruited newborns, children and/or adolescents aged up to 19 years, presenting for the first time to a hospital, emergency department (ED), or primary care facility, regardless of setting. Studies assessing pulse oximeters in screening healthy newborns before discharge, or monitoring, for example, during surgery were excluded.

We included studies with at least one intervention group in which a pulse oximeter reading was taken and at least one control group in which pulse oximetry was not used. We included studies reporting mortality, morbidity (illness severity, ie, pneumonia severity scores, disability at discharge) and length of stay. Descriptive studies were excluded.

We systematically searched the Database of Abstracts of Reviews of Effects, Cochrane, Medion, PubMed, Web of Science, Embase, Global Health, CINAHL and WHO Global Health Library, with no language restrictions (Search terms—see online supplementary appendix I). Study references were checked. Websites of non-governmental organisations, health organisations and development organisations were searched for unpublished reports using 'pulse oximeter' and 'pulse oximetry'. Topic experts were contacted for additional materials.

Studies that were not relevant based on title/abstract were excluded. We read the remaining studies' full texts and excluded those not fulfilling the inclusion criteria. All full texts were read by a second person, and if inclusion was uncertain, a third. We extracted data using a tailored Cochrane data collection form and assessed risk of bias using the Cochrane ACROBAT tool.[23 24]

We intended to calculate risk ratios, mean differences and CI's, and if possible pool data within subgroups and conduct a meta-analysis. However, due to the small number of studies and the study design/outcome variability this was not possible. Instead we narratively describe the evidence using a structured approach while drawing insights where possible, a standard strategy in such situations.

RESULTS

Search results

We found 7992 reports after removing duplicates and screened all titles and abstracts, and the full texts of 17 potentially relevant studies. Five studies,[25–29] all uncontrolled before-after studies (without independent comparison groups), were included (see figure 1).

Risk of bias

Table 1 demonstrates each study's risk of bias.

Intervention effects

Only five eligible studies were included, all uncontrolled before-after studies at high risk of bias; our confidence in the effect estimates is therefore limited with a high level of uncertainty.

Mortality rates

Duke *et al*,[27] reported that mortality rates for children with pneumonia at five Papua New Guinea hospitals decreased by 35% after services were reorganised and pulse oximeters, oxygen concentrators and training were introduced. It is not possible to determine how much of this mortality improvement was due to pulse oximetry versus the provision of training, oxygen systems and other changes.

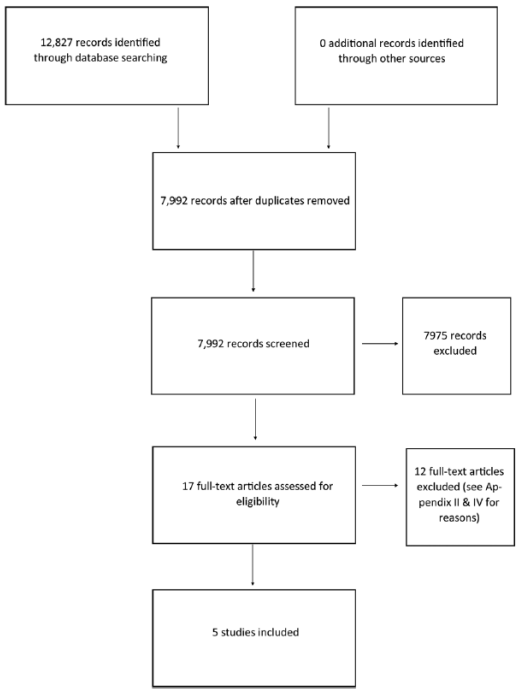

Figure 1 Flow chart showing the study selection process. See online supplementary appendix II for the Characteristics of Included Studies table and online supplementary appendix III for the Characteristics of Excluded Studies table.

Table 1 Risk of bias ratings for each domain for each study

Study	Bias due to confounding	Bias in selection of participants	Bias in measurement of interventions	Bias due to departures from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of the reported result	Overall
Anderson *et al*[25]	Moderate	Moderate	Low	Low	Low	Serious	Serious	Serious
Choi *et al*[26]	Moderate	Low	Low	Moderate	Moderate	Moderate	Low	Moderate
Duke *et al*[27]	Serious	Moderate	Low	Serious	Moderate	Moderate	Moderate	Serious
Maneker *et al*[28]	Moderate	Serious	Low	Low	Low	Serious	Low	Serious
Mower *et al*[29]	Moderate	Serious	Low	Low	Low	Serious	Low	Serious

Risk of bias rating is based on a 4-point scale from low to moderate, serious and critical.

Morbidity

Three studies assessed whether pulse oximeters influence physicians' clinical decision-making. Paediatric physicians assessed children presenting to an ED and decided their treatment before and after obtaining their pulse oximeter results.[25 28 29] Studies defined hypoxaemia differently and their physicians used different oxygen saturation (SaO_2) thresholds to indicate necessary treatment. No independent controls were included, which increased the risk of bias, as did the study designs' accentuation of pulse oximeters' value in the clinical process by presenting oximeter results to physicians after their initial evaluations.

No studies directly measured morbidity; however, two examined whether pulse oximeters facilitate morbidity measurement (illness severity scores and diagnosis). Anderson *et al*,[25] asked physicians to record illness severity assessments, on a 5-point scale, for ill children presenting to the paediatric ward, excluding those with minor orthopaedic/surgical injuries, before and after obtaining pulse oximeter results. Physicians changed 53% of children's scores; two-thirds of these scores were reduced. Physicians in Mower *et al*,[29] changed the diagnoses in 8% of children with SaO_2 <95% and 0.7% of children with SaO_2 ≥95% after receiving pulse oximeter results.

Length of stay and influence on admission rates

In Choi and Claudius,[26] the average time spent in a paediatric ED triage when pulse oximeters were used was 17% less than in the same ED a year previously, when pulse oximeters were not used.

Maneker *et al*,[28] reported that 46/69 children (67%) who had low SaO_2 (SaO_2<92%) had not been clinically expected to have low SaO_2, while 23 (33%) had been expected to have low SaO_2. After obtaining pulse oximeter results, physicians admitted 13/46 (28%) of children with unexpectedly low SaO_2 (who would have been discharged without pulse oximetry) and admitted 1/23 (4%) of children who expectedly had low SaO_2.[28] Mower *et al*,[29] found that after receiving pulse oximeter results, physicians admitted 5 additional children of the 305 who had SaO_2<95% (2%) and 5 additional children of the 1822 who had SaO_2≥95% (0.3%).[29]

Secondary research question

Management plans changed for 19% of children in Anderson *et al*;[25] most of these plans became less intense. In Maneker *et al*,[28] management plans changed for 91% of children who unexpectedly had low SaO_2 (SaO_2<92%); 90% of these were started on oxygen therapy. Management plans also changed for 43% of children who expectedly had low SaO_2; 90% of these were started on oxygen. In Mower *et al*,[29] after receiving pulse oximeter results, physicians ordered new diagnostic tests for 20% of children with SaO_2<95% and for 0.5% of children with SaO_2≥95%; they ordered new treatments for 11% of children with SaO_2<95% and for 1% of children with SaO_2≥95%.

DISCUSSION

Pulse oximeters are routinely used in high-income countries, but are implemented without consistent guidelines of when/how to use them and little research on how their routine use impacts health outcomes or resources. New programmes encouraging pulse oximeter use in low-income countries should address these inadequacies in the evidence base and promote evidence-based decision-making.

Only five studies, all before-after studies at high risk of bias, were identified. Potential dissimilarities in patient/location characteristics existed between time periods in two studies;[26 27] there were no independent controls in three,[25 28 29] and in these, physicians were perhaps more inclined to respond to pulse oximetry because results were given after, not during, initial evaluations (unlike outside study settings). In the study providing mortality data, oxygen concentrators, training and other improvements were introduced with pulse oximeters;[27] while this study points to important effects of improving oxygen therapy systems, from identification to management, it provides only indirect information on possible effects of wide-scale pulse oximetry adoption, for example, primary care facilities for guiding referral. Other challenges in generalising the findings are that the studies were conducted in the USA and Papua New Guinea and none were conducted in primary care facilities. Although the data are drawn from US studies and those conducted over 15 years ago, available results have some value as they suggest how pulse oximeter introduction impacts physicians' decision-making, the key mechanism by which pulse oximetry influences practice.

Study design limitations reduce our confidence in the included studies' effect estimates. However, there is some evidence to indicate that pulse oximetry may lead to improved health outcomes, with lower mortality rates (when combined with improved/adequate oxygen administration) and reduced time in ED triage; pulse oximetry may change physicians' decisions regarding illness severity, and increase hospital admissions related to previously unrecognised hypoxaemia (note: hypoxaemia definitions varied from <92% to 95%). Routine pulse oximetry may also influence diagnostic tests and treatments used. Mower *et al*,[29] argue that physicians generally accurately judged SaO_2 clinically when very high or low, but made more management changes when moderately low.

It is unclear from the literature how pulse oximetry impacts resource utilisation, even though pulse oximetry campaigns focus on low-income settings, where cost-effectiveness is crucial.

In Maneker *et al*,[28] and Mower *et al*,[29] pulse oximetry increased resource use through increased admissions and oxygen

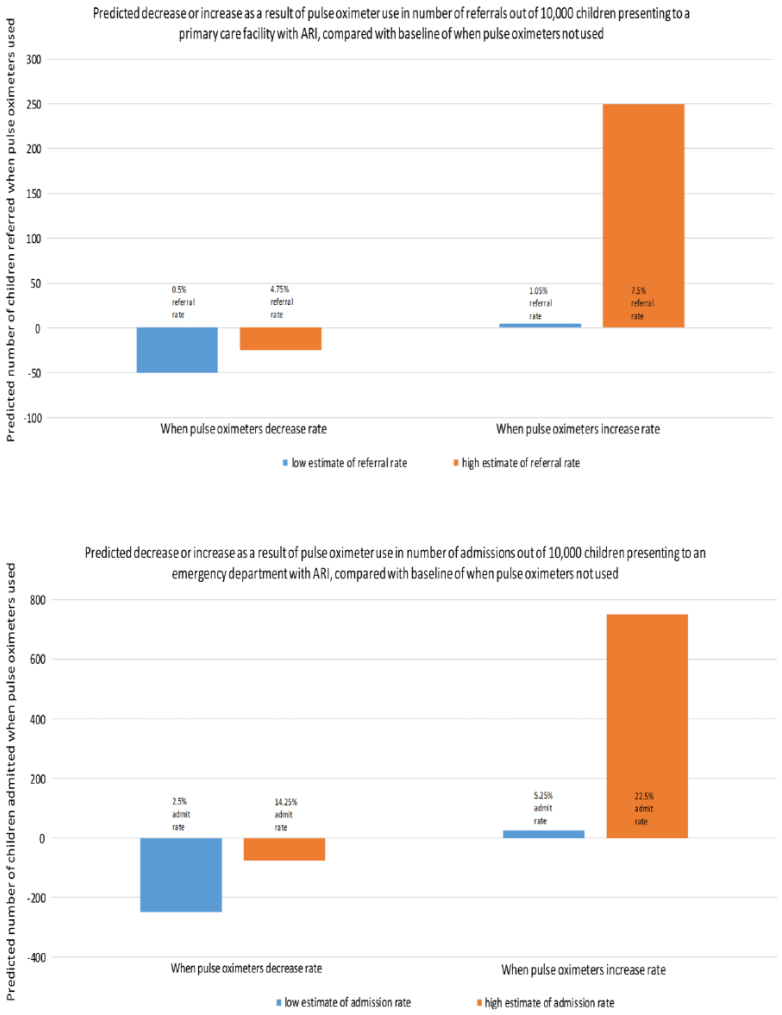

Figure 2 Simple, hypothetical illustration of introducing pulse oximetry into primary care or walk-in clinical settings illustrating the trade-offs that may be apparent in terms of increased or decreased referral or admission rates based on plausible (low and high) estimates of existing rates and true prevalence of hypoxaemia. Note that in low-income countries children often have multiple acute respiratory infections (ARI) episodes per year. The estimates for the baseline (when pulse oximeters are not used) were the following: low estimate for referral rates from primary care facilities: 100 (1%); high estimate: 500 (5%); low estimate for admission from emergency department (ED): 500 (5%); high estimate: 1500 (15%). Referral and admission rates for when pulse oximeters are used were estimated by assuming an increase or decrease in primary care referrals/ED admissions of 5–50% over or below the baseline referral/admission rates. Hypoxaemia prevalence in children aged 7 days–36 months presenting to an ED with ARI has been shown to be as high as 59%[31] (when hypoxaemia defined as SaO_2<91%) so these high estimates for referral/admission rates are reasonable. Referral/admission rates would be higher in a population if: the true hypoxaemia prevalence in the population is higher (eg, due to high altitude, seasonal effects on bronchiolitis, predisposing environmental factors for asthma); a larger proportion of hypoxaemic children are being missed by clinical evaluation; or higher thresholds are used to define hypoxaemia. The converse of these conditions would lead to lower referral/admission rates, as would a reduction in the number of false-positives as a result of improved accuracy of hypoxaemia diagnosis over clinical signs.

therapy for children with otherwise undetected hypoxaemia. Pulse oximetry led to reduced resource utilisation in two studies: in Anderson *et al*[25] two-thirds of children whose illness severity scores changed were then considered less severely ill, and two-thirds of children whose management plans changed were then managed less aggressively; in Choi and Claudius,[26] pulse oximetry led to reduced triage time.

Pulse oximetry could facilitate quicker diagnosis, so effective treatment starts earlier and recovery likelihood increases, reducing future resource use. Oximetry can reduce resource waste by indicating when to end treatment, and by decreasing false-positives. However, in Schroeder *et al*,[30] hospital stays were on average 1.6 days longer because of pulse oximetry as 26% of children met discharge criteria except needing oxygen according to pulse oximeters. If additional treatment was unnecessary (eg, inappropriate thresholds were used), then resources were wasted (as the authors assumed). However, if pulse oximetry enabled detection of hypoxic children who would not otherwise obtain treatment, then the additional resources were justified.

Although not discussed here, pulse oximetry also has important resource implications in outpatient facilities, where hypoxaemia prevalence in children, while lower than in hospitals, is still considerable (eg, 4–12%),[2] and where pulse oximetry could facilitate timely recognition of necessary care or referral to hospital. Figure 2 illustrates the range of effects of introducing pulse oximetry.

Randomly assigning health facilities to pulse oximeter introduction (with training) or no pulse oximetry could provide robust data on resource use (admissions, diagnostic tools, treatments, referrals, length of stay), health outcomes (mortality, morbidity, re-presentations), and which thresholds, if any, would be most effective for treatment initiation, if studies were sufficiently large. Such pragmatic studies could be done alongside implementation programmes and could elucidate whether pulse

Table 2 Summary of findings

Pulse oximeters versus no pulse oximeters to inform diagnosis and treatment (excluding operative surgical care)

Population: newborns, children and adolescents aged up to 19 years
Intervention: pulse oximeter readings
Control: populations with no pulse oximeter readings
Outcomes: mortality rates, morbidity, length of hospital stay

Outcomes	Overall outcome difference between control and intervention group	Number of participants by outcome (studies)	Relative effect (with 95% CI)	Absolute effect (with 95% CI)	Quality of the evidence—Grade
Mortality rates	The introduction of pulse oximeters alone may lead to a reduction in mortality rates.[27]	11 291[27]	RR: 0.648 (0.533 to 0.788)	Reduction of 1.75% (1.101 to 2.398) or 17 fewer deaths per 1000 patients	Very low*
Morbidity:	When pulse oximeter results are obtained in the ED, the assessed degree of illness and the diagnosis for children may be different than if pulse oximeter results are not obtained. This is especially the case for children who do not have a diagnosis of 'well', 'minor orthopaedic injuries' or 'minor surgical injuries', and/or is more likely in children who have low SaO_2 values.[25 29]	2564[25 29]	n/a	n/a	Very low†
Length of hospital stay	The introduction of pulse oximetry into triage may decrease the average time children spend in triage and may increase the proportion of hypoxic children who are admitted.[26 28 29]	622[26 28 29]	Time spent in triage: Mean difference: 50 min (5.405 to 94.595) Proportion of hypoxic children admitted: n/a	Time spent in triage: 17 fewer minutes spent in triage per 100 min Proportion of hypoxic children admitted: n/a	Very low‡
Secondary research question: treatment and management	When pulse oximeter results are obtained in the ED, the management plans for children may be different than if pulse oximeter results are not obtained. This is especially the case for children who do not have a diagnosis of 'well', 'minor orthopaedic injuries' or 'minor surgical injuries', and/or is more likely in children who have low SaO_2 values, particularly if these are unexpectedly low.[25 28 29]	2633[25 28 29]	n/a	n/a	Very Low§

See online supplementary appendix IV for a more detailed summary of findings table.
*Non-controlled before-after study: Study limitations—there is a high risk of bias as the Duke *et al*[27] study had a serious risk of bias, due mainly to the fact that oxygen concentrators and training were introduced into the study hospitals concurrently with pulse oximeters so it is not possible to determine how much of the change in mortality rates shown in the study was due specifically to pulse oximeter use; indirectness—the study was looking at the impact of the introduction of pulse oximeters and oxygen concentrators on mortality rates, rather than just the introduction of pulse oximeters alone; imprecision—only one study (and it did not report CIs for the measure of interest); this outcome has therefore been downgraded from Low to Very Low.
†Non-controlled before-after studies: Study limitations—there is a high risk of bias as both of these studies had a serious risk of bias, because the physicians in both studies were aware of the intervention status of the participants and so may have been more likely to take the pulse oximeter results into account than had they received the pulse oximeter results during their initial evaluations; in addition the authors of Mower *et al*[29] excluded 20% of children who could have been included in the study, potentially affecting the results, and the authors of Anderson *et al*[25] excluded a subgroup of children from the analyses when it became evident that pulse oximeter results did not impact their management, so the study's results of pulse oximeter impact were exaggerated; indirectness—the changes in degree of illness and diagnosis shown in these studies are not actual changes in morbidity, they are changes in physicians' perceptions of morbidity; also both studies were looking at different suboutcomes and different subgroups from each other, most of which were not directly relevant to, or only partially relevant to, the review; imprecision—only two studies (neither of which reported any CIs); this outcome has therefore been downgraded from Low to Very Low.
‡Non-controlled before-after studies: Study limitations—there is a high risk of bias as two of the studies had a serious risk of bias, because the physicians in both studies were aware of the intervention status of the participants and so may have been more likely to take the pulse oximeter results into account than had they received the pulse oximeter results during their initial evaluations; in addition 20% and 32% of potential participants were not included in the Mower *et al*[29] and Maneker *et al*[28] studies, respectively, potentially affecting the results; indirectness—the outcomes investigated in the three studies (length of stay in emergency department (ED) triage, and % admitted) are indirectly related to but not exactly the same as, the outcome of length of hospital stay; imprecision—only three studies (none of which reported any CIs); this outcome has therefore been downgraded from Low to Very Low.
§Non-controlled before-after studies: Study limitations—there is a high risk of bias as all three of these studies had a serious risk of bias, because the physicians in all three studies were aware of the intervention status of the participants and so may have been more likely to take the pulse oximeter results into account than had they received the pulse oximeter results during their initial evaluations; in addition 20% and 32% of potential participants were not included in the Mower *et al*[29] and Maneker *et al*[28] studies, respectively, potentially affecting the results; also the authors of Anderson *et al*[25] excluded a subgroup of children from the analyses when it became evident that pulse oximeter results did not impact their management, so the study's results of pulse oximeter impact were exaggerated; indirectness—the secondary research question considered the impact of pulse oximeter use on the proportion of children receiving oxygen therapy—only one of the studies actually reported the number of children in both groups who received oxygen therapy while the other two studies only reported results on outcomes that are related to oxygen therapy, by, like oxygen therapy, being examples of treatment and management; also all three studies were looking at different suboutcomes and different subgroups from each other, most of which were not directly relevant to, or only partially relevant to, the review; imprecision—only three studies (none of which reported any CIs); this outcome has therefore been downgraded from Low to Very Low.

oximetry impacts resource use and health outcomes within cost-effectiveness analyses.

If evidence suggests pulse oximetry increases resource utilisation then health workers, facility managers and public health practitioners would need to weigh cost-benefit trade-offs between using scarce resources on pulse oximetry or on other interventions. Context-specific formal cost-effectiveness analyses could be performed to help address these issues but these are rarely done when technologies are introduced into low-income countries' health systems. Such research should be independent and transparent evaluations feeding into wider, evidence-based and inclusive processes for decision-making on resource allocation within health systems.

More research is also needed on the best ways to use pulse oximeters, particularly concerning SaO_2 thresholds.

In high-income settings, disease management guidelines rarely recommend SaO_2 thresholds for diagnosing, evaluating or monitoring children.[12 13] When specific SaO_2 thresholds are recommended, they differ across organisations, even though WHO's 2012 Recommendations for Management of Common Childhood Conditions provide clear guidance that oxygen be administered if SaO_2<90% (for children at ≤2500 m).[14 15] Conversely, the Canadian Paediatric Society warns "it is important to recognize that setting arbitrary thresholds for oxygen therapy will influence admission rates".[16] Setting thresholds is complicated because pulse oximeter results may not be considered in isolation from clinical findings, SaO_2 can naturally fluctuate over a day, and studies show that 'healthy' SaO_2 differs by age and altitude.[20–22 32] A few studies have investigated whether outcomes are comparable when thresholds higher than WHO's <90% are used: Cunningham *et al*,[33] found cough resolution time in children with bronchiolitis was equivalent when a <94% or <90% threshold was used for oxygen therapy while Lazzerini *et al*,[34] found that hypoxaemia predicted elevated mortality risk in children with acute lower respiratory infection when a <92% or <90% hypoxaemia threshold was used. It is therefore perhaps unexpected that no studies have examined health system consequences of implementing the WHO guidance of using SaO_2<90% thresholds.

In absence of clear guidelines, opinion differs on which thresholds should indicate hypoxaemia and prompt admission, referral, oxygen therapy or other treatments. When emergency physicians were surveyed, there was considerable variability in the lowest SaO_2 for which they would discharge a 2-year-old with pneumonia and a 10-month-old with bronchiolitis.[18] Maneker *et al*[28] and Mower *et al*,[29] defined low SaO_2 as ≤92% and <95% respectively, thus reducing results comparability.

Threshold choice can substantially impact health system outcomes; thus in Schuh *et al*'s[35] randomised clinical trial of infants (excluded from this review because all children received pulse oximeter readings), admission rates were sensitive to small saturation differences: 41% of children in the control group were admitted within 72 h versus 25% of children whose displayed SaO_2s were artificially increased by 3%.

CONCLUSIONS

Pulse oximeters are routinely used in high-income countries and international organisations are investing in programmes to promote pulse oximetry in low-income countries, but there is little evidence, from any region or setting, on the impact or optimal use of pulse oximeters when children present to a health facility. More research is needed on how pulse oximetry impacts health outcomes and services, how knowledge of SaO_2 should be integrated with other clinical findings, whether defining 'one-size fits all' thresholds is possible or even useful, for hypoxaemia and in diagnosing/monitoring specific diseases, and how pulse oximetry affects resource utilisation. Such pragmatic research could accompany pulse oximeter implementation efforts and would provide much needed evidence.

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Contributors AJE drafted the initial protocol with the assistance of SS and ME; AJE carried out the systematic review, SS and ME read through full texts of potential studies and advised on the bias assessments; AJE drafted the initial report and all authors contributed to its development and approved the final version.

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