



Understanding the Challenges Nurses Encounter with Monitoring Technologies in a NICU

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ABSTRACT

A neonatal intensive care unit (NICU) provides an optimal environment for the care of preterm babies. Bedside nurses are fundamental to this care provided to preterm babies in the NICU. Modern NICUs are technology-intensive space, instrumented with several monitoring technologies to help the nurses track the babies in their care. These technologies help the nurses in a way that is essential for the successful operation of the NICU. To understand how these monitoring technologies function in the NICU from the viewpoint of the nurses, we conducted semi-structured interviews with seven nurses who work at a NICU in the US. We then performed a thematic analysis on the interviews and we found that, despite the utility of the monitoring technologies, they also pose several challenges to the nurses in performing their duties. More specifically, we discovered that: (1) all elements of the monitoring technologies posed a challenge in some way; (2) in a few specific situations, the nurses were able to make up for some of these challenges; and (3) the nurses suggested improvements to all elements of the monitoring technologies. Based on these findings, we describe six areas of future research that argue for the design of monitoring technologies as a way to empower nurses. These include: improved vital signs monitoring that facilitate kangaroo care, using voice to manage alarms, video feeds controlled by nurses in the patient rooms, giving more control over the alarm sounds to the nurses, having a common interface and leveraging augmented reality to help the nurses control the monitoring technologies.

KEYWORDS

NICU; nurses; monitoring technologies; alarms; NICU phones; workflow

1. Introduction

The aim of the neonatal intensive care unit (NICU) is to provide an environment that is optimal for the health, recovery, and growth of preterm babies (defined as those born before 36 weeks of gestation) or full-term newborns with severe health issues (Hauser et al., 2020). Each baby in the NICU is cared for by a team, which includes the physician, bedside nurse, lactation consultant, occupational therapist, respiration therapist, social worker, case manager, and, of course, parents. Bedside nurses, who care for the baby during their stay in the NICU, are the beating heart of the care provided in the NICU. *In the rest of the paper, for expediency, we use the term nurse to mean a bedside nurse, unless otherwise specified.*

A typical nurse in the NICU has several babies in their care in a given shift (Rogowski et al., 2015). This brings about the need for the nurses to be aware of the state of all the babies in their care at any given time. Consequently, the NICU is a technology-intensive space instrumented with several of what we refer to as **monitoring technologies** to help the nurses track the babies in their care. We use the term *monitoring technologies* in this paper in a broad sense, to denote the collection of technologies that NICU nurses

use to: (1) know and track the health status of the babies in their care and (2) receive audio and visual warnings that bring the nurse's attention to situations where the baby's health is potentially deteriorating. These monitoring technologies greatly assist the nurses by automating many of the tasks they need to perform in caring for the babies. *However many elements of the monitoring technologies in a NICU are repurposed from devices used in the rest of the hospital (i.e., mostly for adult patients).*

Prior work at the intersection of monitoring technologies and the NICU has generally focused on: (1) improving baby monitoring with novel monitoring technologies (H. Chen et al., 2020; Wang et al., 2019); (2) reducing false alarms (Bitan et al., 2004; Bitan et al., 2004; Cabrera-Quirós et al., 2021; Varisco et al., 2021); and (3) improving the parents' experience and interaction with the baby in the NICU (Antinora et al., 2023; Kilcullen et al., 2020; Lakshmanan et al., 2019; Lee et al., 2011; Liu et al., 2011; Mburu et al., 2018). Studies focused on NICU nurses have looked into their use of various forms of technologies, such as teleconferencing, (Qavi et al., 2002); robot-nurse interaction (Taylor et al., 2019); using AI to simplify their charting needs (Hunter et al., 2012); and their use of digital technologies in and out of the NICU (Shrestha et al., 2022). However, to

our surprise, no prior study focuses on how the nurses perceive, use, and struggle with the existing monitoring technologies in the NICU. To the best of our knowledge, the present work is the first study to take a comprehensive look at NICU nurses' experiences with the existing monitoring technologies in the NICU.

To understand how these monitoring technologies function in the NICU *from the viewpoint of the nurses*, several authors first conducted an informal visit of a level-IV NICU (which provides the highest level and most acute care) in a hospital in the US to get a general sense for the NICU as a care space. Subsequently, the first author formally conducted one-on-one semi-structured interviews with seven (7) nurses who work at the NICU. An initial pass over the interview transcripts demonstrated a recurring theme of the nurses having issues with monitoring technologies, especially as the number of babies in their care increased. Therefore, for the formal thematic analysis of the interviews, we realized that we had to consciously look for the challenges encountered by the nurses in using the monitoring technologies primarily to answer the following research questions: (RQ1) What challenges do the nurses perceive when using monitoring technologies in a NICU? (RQ2) Are the nurses able to overcome the challenges posed by the monitoring technologies in a NICU? If so, how and under what circumstances? (RQ3) What improvements, if any, to monitoring technologies in the NICU would the nurses suggest?

Overall we found that all elements of the monitoring technologies impeded the nurses' ability to perform their duties in some way. Further we found that, in some limited situations, nurses were able to rely on their experience to find interesting ways to cope with the challenges that the monitoring technologies posed. Given the difficulties the monitoring technologies posed to the nurses, the latter also suggested several improvements to the monitoring technologies. We end the paper by arguing that one of the ways to address these problems is to rethink the design of monitoring technologies in a way that empowers and centers NICU nurses. We thus discuss six broad areas of future research aimed at designing monitoring technologies that empower NICU nurses. Taken together, our findings provide valuable insights for the human-computer interaction (HCI) community to understand the needs, limitations, and expectations around the use of monitoring technologies by bedside nursing professionals in a NICU setting.

2. Related work

The last two decades have seen studies that examine various aspects of nursing and the NICU. However, to the best of our knowledge, no prior work has focused on developing a broad understanding of the nurses' lived experience with respect to their use of the various monitoring technologies in the NICU. The extant work at the intersection of nursing, the NICU, and monitoring technologies can be grouped into three broad categories, which we describe below. We start with a summary of the work focused on nurses and nursing (broadly speaking) in the literature. We follow this with a

more general literature review on nursing and the use of technology specifically in the NICU.

2.1. Nurse-focused research in the associated literature

The HCI and Computer Supported Cooperative Work (CSCW) literature on NICU nurses is quite sparse. The extant work in this domain has primarily been in three areas: understanding how the nurses use personal digital devices, designing digital tools to aid the nurses in specific tasks, and understanding the nurses' workflow in the medical ecosystem.

With respect to understanding nurses' use of digital technologies, work has been done to consider issues such as privacy risks (Shrestha et al., 2022), chat use (Karusala et al., 2020), clinical decision support use (Febretti et al., 2014; Kaltenhauser et al., 2020; Klüber et al., 2020), use of digital charts in patient rooms (Asan et al., 2017), the use of teleconferencing (Qavi et al., 2002), and the use of NFCs (near-field communication) by nurses (Alabdulhafith et al., 2016).

In the context of designing technologies to help the nurses, prior work has focused on issues such as robot-nurse interaction in care settings (Alves-Oliveira et al., 2021; Taylor et al., 2019), developing shift summaries for NICU nurses (Hunter et al., 2012), and designing for peripheral interactions in a NICU (Cabral Guerra et al., 2019).

Finally, prior work focused on understanding the nurses' workflows in the medical ecosystem has covered topics such as nurses as designers in the medical environment (Abranches et al., 2019; Albrecht-Gansohr et al., 2023; Lakshmi & Arriaga, 2022; Tang & Carpendale, 2007), nurses' workloads in emergency departments (Kim et al., 2019), understanding human errors in medical settings (Sarcevic et al., 2012), how NICU nurses deal with substance-exposed pregnancies (Welborn et al., 2020), and nurses' reactions to alarms produced in patient rooms (Bitan et al., 2004);

None of the existing work in the fields of HCI and CSCW has focused on understanding the challenges of monitoring technologies for nurses in a NICU, as we do in this paper.

2.2. Understanding nursing in a NICU

Recent years have also seen much work with respect to nursing in the NICU. We divide these studies into two main categories: understanding how nurses operate within a NICU under various situations and understanding and managing alarm fatigue in the NICU.

Some of the work in the context of understanding how nurses operate include: nurses' interpretation of infant pain (Howard & Thurber, 1998); the promotion of breastfeeding by NICU nurses (Cricco-Lizza, 2011); the delivery of palliative care by NICU nurses (Kain, 2006); how an individual-room NICU layout affects nurses (Cone et al., 2010); nurses' opinions on using live video streams for parent/child bonding in the NICU (Kilcullen et al., 2020); burnout of nurses in the NICU (Aytekin et al., 2013; Profit et al., 2014); stress and social support among nurses in the NICU (Bry &

Wigert, 2022); understanding the nurse-parent relationship and communication (Jones et al., 2007; Reis et al., 2010; Wigert et al., 2013); and how nurses implement family-centered care in the NICU (Coats et al., 2018; Gilstrap, 2021; Griffin, 2006).

Similarly, alarm fatigue, which is a big part of the nursing experience in the NICU, has been studied in detail as well (Bourji et al., 2020; K. R. Johnson et al., 2017; Simpson & Lyndon, 2019). Most of the work in this regard has focused on finding ways to reduce false alarms, including approaches that: predict when nurses should respond to an alarm (Cabrera-Quirós et al., 2021), perform workflow optimization to reduce false alarms (Varisco et al., 2021); suggest updates to alarm settings (K. R. Johnson et al., 2018; Ketko et al., 2015; Varisco et al., 2021); use a pressure-sensitive mat to detect motion and the resulting false alarms (Kyrillos et al., 2021); educate nurses to use the monitoring equipment correctly (Pirrucello & Rubarth, 2015); and the use point-of-care quality improvement principles to reduce false alarms (Patel et al., 2022).

Although the literature on managing alarm fatigue does consider some individual elements of monitoring technologies, i.e., alarms, none of them focuses on understanding in a comprehensive manner the nurses' experience with the larger monitoring technologies in a NICU setting, which we do in this paper.

2.3. Digital technologies for the NICU environment

The last few years have seen a considerable amount of work on developing technologies for the NICU. This includes work focused on developing vital-sign monitoring technologies for neonates, technology for helping parents in the NICU, educational tools for the parents, and technologies to help nurses with their duties.

Examples of work done on developing vital-sign monitoring technologies include multimodal sensing platforms (H. Chen et al., 2020; Kwak et al., 2021; Nivetha & Kumar, 2020), EKG monitors (Fossi et al., 2006), heart rate monitors (Cay et al., 2022; Cay et al., 2021), oxygen saturation monitors (W. Chen et al., 2010), respiration monitors (Cay et al., 2022), temperature monitors (W. Chen et al., 2010), and sleep monitors (Wang et al., 2019).

The NICU is unique in that parents play a major role in the care of the patient (i.e., the baby) unlike most other units of the hospital. A lot of prior work with respect to NICUs has therefore aimed at helping parents in the NICU. This includes mobile applications to facilitate the baby's transition to the home (H. N. Kim et al., 2015; Lakshmanan et al., 2019; Lee et al., 2011), co-designing with nurses and parents technologies to support parents (H. N. Kim et al., 2015; Mburu et al., 2018), understanding, supporting and enhancing the parental experience while in the NICU (Bonner et al., 2017; Choi & Bakken, 2006; Craig et al., 2015; Doron et al., 2013; Erdei et al., 2023; A. N. Johnson, 2008; Ranu et al., 2021), wearables that facilitate breastfeeding (Clarke-Sather & Naylor, 2019), and connecting NICU babies with their remote families (Antinora et al., 2023;

Hawkes et al., 2015; Joshi et al., 2016; Pompilio-Weitzner et al., 1998; Rhoads et al., 2015; Rhoads et al., 2012; Yeo et al., 2011).

Educational technologies for parents has also been considered in the literature with work done on: educating women about preterm risk (Jani et al., 2021) and education technology to mediate kangaroo care (Nascimento & Teixeira, 2018).

Finally, some work has also been done on designing technologies helping the nurses with their duties in a NICU. This includes work such as: reducing noise from auditory alarms for babies in the NICU (Freudenthal et al., 2013), breast milk management (Dougherty & Nash, 2009), and facilitating and simulating kangaroo care with technology and without the presence of the parent (Claes et al., 2017; Hauser et al., 2020; Kommers et al., 2019; Vitale et al., 2021).

Though many of these studies do consider nurses, their focus is mostly on the interactions between the nurses and the babies and/or the babies' families and not on providing a detailed look at the nurses' experience with a broad set of monitoring technologies in the NICU, as we do in this paper.

3. Study methodology

In this work, we interviewed *nurses* who worked at a Level-IV NICU in a hospital in the US. These nurses were highly experienced and were able to provide a global perspective on their use of monitoring technologies in the NICU. All interviews were conducted over Zoom because of the COVID-19 pandemic and to accommodate the nurses' busy schedules. All participants were compensated for their time. The interview protocol was approved by the institutional review board (IRB), the ethics board of the University of Rhode Island.

Our original intention when we conducted the interviews was to broadly understand the nurses' experiences in the NICU with respect to the monitoring technologies used in the space. Before conducting the interviews, we wanted to get an overview of how a NICU operates. Therefore, several members of the research team individually and informally visited the NICU to get a sense for the space and its basic workflow (an overview of the nurses' duties with respect to the babies and their parents). This allowed us to develop appropriate research questions for the interview study. Next we conducted semi-structured interviews of the nurses in the NICU. The interview study opened with a brief introduction of our aims. We followed this up with questions in the following categories:

- Category 1: What are the details of the nurses' duties with respect to the babies under their care?
- Category 2a: How are the various physiological signals measured, viewed, interpreted, and used in care for the baby?
- Category 2b: What are the various types of interventions administered to the baby in the NICU?

- Category 3a: How do the nurses simultaneously keep track of all the babies under their care?
- Category 3b: How do the nurses deal with the alarms and alerts produced?
- Category 4a: What are the details of the nurses' duties with respect to the parents of the babies under their care?
- Category 4b: How do the parents react to the monitoring technologies (broadly defined) in the NICU?
- Category 5: What improvements would the nurses like to see in the NICU with respect to monitoring technologies (broadly defined) and their own workflow?

After the interviews, we also followed up via email with a few participants to further clarify some of their responses.

A total of seven (7) NICU nurses participated in the interviews. All seven nurses worked at the hospital's NICU at the time of the interviews and had done so for several years. Table 1 shows the demographic information for the nurses we interviewed. After the user study, the collected Zoom recordings were transcribed.

As we did an initial pass over the transcript of the interviews we noticed that a recurring theme in the interviews was some of the difficulties the nurses were having with the monitoring technologies used in the NICU, especially as the number of babies in their care increased. Therefore, for the formal thematic analysis of the interviews, we realized that we had to consciously look for the challenges encountered by the nurses in using the monitoring technologies primarily to answer the following research questions: (RQ1) What challenges do the nurses perceive when using monitoring technologies in a NICU? (RQ2) Are the nurses able to overcome the challenges posed by the monitoring technologies in a NICU? If so, how and under what circumstances? (RQ3) What improvements, if any, to monitoring technologies in the NICU would the nurses suggest?

Table 1. Demographic information of the NICU nurses interviewed for our study.

ID	Gender	Time as a NICU nurse	Time spent in the NICU
P1	Female	3.5 years	36 h/week
P2	Female	21 years	32 h/week
P3	Male	16.5 years	24 h/week
P4	Female	19 years	32 h/week
P5	Female	24 years	32 h/week
P6	Female	6.5 years	36 h/week
P7	Female	2 years	32 h/week

We applied Braun and Clark's 6-step recursive approach to thematic analysis, as described in Byrne (2022). The first three authors completed the coding and analysis in a collaborative manner, aiming to achieve a richer interpretation of meaning than attempting to achieve consensus would produce. The coding and theme development were done inductively and evolved throughout the analytic process. Table 2 lists the final themes that were generated from this analysis. The results of our analysis are summarized in the findings sections of the present paper, which can be found in Sections 5–7. Before we delve into the findings, however, we provide an overview of how a technologically-intensive NICU operates, which we believe is essential to understand the findings.

4. An overview of the NICU and the nurses' duties

Before we get into answering our research questions, we provide a quick overview of a technologically-intensive NICU environment and the various duties that nurses perform in this space. This section provides an overview of, among other things, how monitoring technologies are used within the NICU. Monitoring technologies provide the nurses with a variety of abilities that are crucial for them to perform their duties effectively. In this section we therefore present information on how these technologies are used by the nurses in performing their duties. This section can be seen as providing the context necessary to understand our findings, which discuss the challenges presented by the same monitoring technologies.

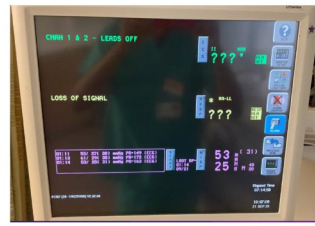
Nurses in a NICU work as part of a care team for the baby (Rogowski et al., 2015). The care team at the hospital where our participants work consists of: the bedside nurse, parents, physician, respiratory therapist, social worker, lactation consultant, occupational therapist, and case manager. The nurses' duties in a NICU are varied and highly complex. For the purposes of this paper, we focus on the *typical duties* of the nurses in the NICU. Information in this section was obtained from two sources: (1) the observations made during the informal visit to the NICU and (2) responses obtained during the interviews. The observations made during the informal visit are limited to providing information about the extant physical setup of the NICU, whereas the responses from the interviews provided details of the duties and prevalent workflow. Quotations are provided (with edits for brevity and clarity), as appropriate, for information

Table 2. The final set of themes that emerged from the analysis of the interviews.

Theme	Sub-theme	Definition
Overview of the NICU	Background	Background information about the NICU and its workflow
	Nurses' Duties	Overview of duties toward the baby and parents
	Parent's presence	Affect of the presence of parents on the nurses' duties
Challenges in the NICU	Sensing challenges	The deployment, use, and management of sensors measuring physiological signals from the baby
	Tracking challenges	Simultaneously monitoring multiple babies using monitoring technologies and the issues that arise as a result
	False alarms	All the negative effects false alarms in the NICU
Utilizing experience		How nurses use their experience to handle some of the challenges
Improvements to the monitoring technologies		Suggestions from the nurses about how they would like to see the monitoring technologies improved



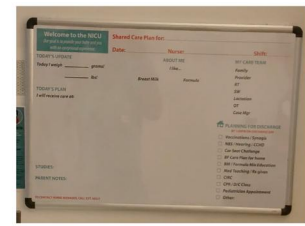
a) A typical NICU room with an incubator bed (older babies – close to full term – may have an open crib)



b) A typical patient monitor in a NICU room



c) A nurse's station in a NICU room



d) A daily baby health status update board for the parents



e) Space for infusion pumps and O₂ in a NICU room



f) The NICU room refrigerator, storage, and supplies cart



g) The typical NICU room with sliding glass door



h) Windows in a NICU room for visibility from outside



i) A seating area for the parents (with a privacy curtain) to rest and bond with the baby

Figure 1. A typical NICU patient [baby] room and its various salient features, such as an incubator bed; a patient monitor; a charting computer; a health status display board; space for various accessories such as infusion pumps, oxygen, refrigerator, and supplies; a sliding door and privacy curtain; and a sofa for parents to spend time with the baby in the room. (a) A typical NICU room with an incubator bed (older babies – close to full term – may have an open crib). (b) A typical patient monitor in a NICU room. (c) A nurse's station in a NICU room. (d) A daily baby health status update board for the parents. (e) Space for infusion pumps and O₂ in a NICU room. (f) The NICU room refrigerator, storage, and supplies cart. (g) The typical NICU room with sliding glass door. (h) Windows in a NICU room for visibility from outside. (i) A seating area for the parents (with a privacy curtain) to rest and bond with the baby.

obtained from the interviews. The details of the individual duties that a nurse has to do might vary from NICU to NICU, depending on the prevalent workflow and technology use but the overall set of duties generalize.

4.1. NICU room setup and assignments

Historically the NICU where the participants work was set up in what is known as bay style, where all the babies were in one large room. Each nurse was assigned up to four babies since they were in one large room: “When I first started, four patients was the norm. We had what we called a step-down or continuing care nursery and it was traditionally four patients in that area.” (P4). The NICU where our participants work is currently (as of 2009) organized as a collection of individual rooms where each baby is assigned to a room (except in the case of twins, who may be placed in one room together). Each room is fully instrumented to monitor and care for the baby. It includes, among other things: a bed for the baby, supplies (gloves, diapers, etc.), a

refrigerator for storing breast milk and medicine, infusion pumps, and an oxygen line (see Figure 1(a,e,f)). The baby is monitored using a *patient monitor*, which is a computer that processes and displays the physiological signals from the baby and initiates warnings in the form of audible and visible alarms (see Figure 1(b)).¹ Each room has a computer that the nurse uses to perform charting (i.e., data entry into the hospital electronic health record (EHR)) to track the baby's state during their stay in the NICU (see Figure 1(c)). The room also provides a sofa with privacy curtains around it, where the family can spend time with the baby (see Figure 1(g,i)). The family can see updates about the baby's health status on the daily baby board, which is written on an erasable white board (see Figure 1(d)). Typically the rooms have glass walls that allow the nurse to see the patient monitor and the baby from outside the room (see Figure 1(h)). The rooms are organized into *neighborhoods*: “So the way it's set up, there's four hallways on each floor and each hallway has eight to ten rooms and you'll have three to four nurses in each hallway. We call it a

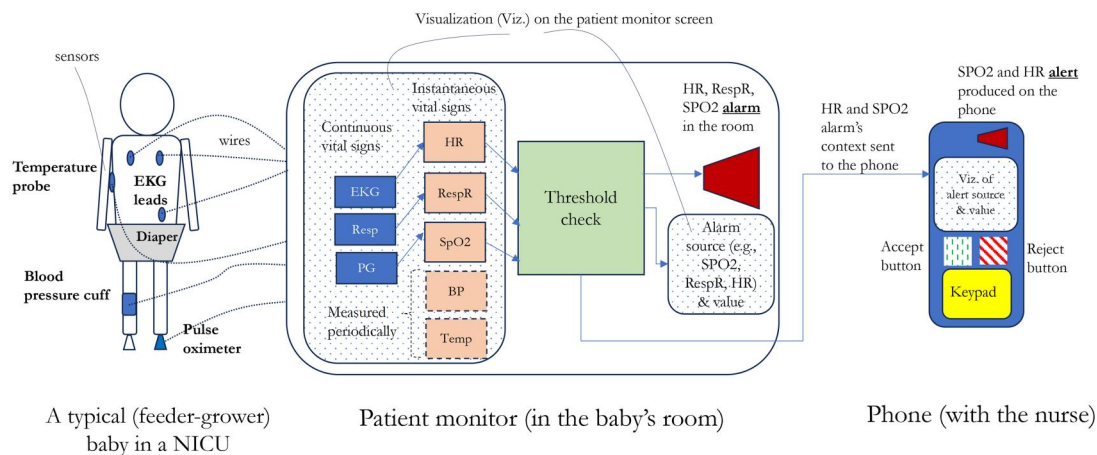


Figure 2. A Diagrammatic overview of a common configuration of *monitoring technologies* in the NICU (where our participants work) for a baby at the feeder-grower stage. We use the generic term *sensors* to mean wired leads/electrodes/cuffs used to measure the baby's vital signs, all of which send their measurements to a patient monitor. The patient monitor produces a warning, via an audiovisual *alarm*, anytime a vital sign goes outside the preprogrammed acceptable range. For certain vital signs, the alarm context (i.e., the location and cause of the alarm) is also sent as an *alert* to a phone carried by the nurses, who often take care of multiple babies and thus may not be near the alarming baby.

neighborhood." (P4). Nurses also have designated spaces between every two adjacent rooms in the hallway called nurse's stations, which they can use while they are not in any of the babies' rooms. These spaces have a clear and unobstructed view of the babies inside the two adjacent rooms. Since the COVID-19 pandemic, no one from the extended family is allowed into the NICU anymore: "Since COVID, there's no visitation. It's only the parents can come in, no one else." (P4).

In the NICU where the participants work, nurses can be assigned up to *four* babies to care for during their shift. The maximum assignment was supposed to be three babies per NICU nurse. However, this number has increased in recent times to four: "We moved to the new unit, which is all single-patient rooms, and it was never supposed to go over three patients - never was supposed to but it does go. So if they're lower acuity babies who don't need a lot of hands-on time, then they'll be in a three-to-four baby assignment." (P4). A four-baby assignment is an unusually high workload for the nurses – the result of a severe NICU nurse shortage in the US – which enormously increases the stress on them (Nurse Shortage, 2023). According to a 2015 study, the average number of babies per nurse in NICUs in the US, for low-acuity babies, was 2.78 babies (Rogowski et al., 2015). The hospital where our participants work was already above average in its baby assignment of three, which has now become even worse because of the shortage: "So, well, we're not supposed to have four but with our staffing shortage, that has become one of our new norms lately." (P5).

4.2. Typical configuration of monitoring technologies in a NICU

As stated before, the NICU is a technology-intensive space instrumented with, among a variety of other technologies, several **monitoring technologies** that: (1) help the nurses track the babies in their care and (2) notify the nurses, via warnings, when their health deteriorates. Below we present an overview of how the typical monitoring technologies are

configured in the NICU where the participants work. Figure 2 provides an overview of the main elements of the monitoring technologies that we will be discussing in the rest of the paper. Of course, the needs of every baby in a NICU are often unique. However, for expediency, this figure represents a common configuration of the monitoring technologies in the NICU where the baby is at what is called the feeder-grower stage: "feeder-growers... are on minimal settings for respiratory devices" (P7).

Nurses instrument the babies with *sensors*² to collect their *vital signs*, which include: (1) the *continuous* waveforms for electrocardiogram (EKG), plethysmogram (PG), and respiration and (2) *instantaneous* measurements of heart rate (HR), respiration rate (RespR), blood oxygenation saturation percentage (SPO₂), blood pressure (BP), and body temperature (Temp). HR and RespR are both measured via the EKG sensors whereas the pulse oximeter measures the PG wave and instantaneous SPO₂ percentage: "It's a small little wrap that's kind of like, it kind of looks like a Band-Aid almost and it wraps around the foot. Then we put a little cushiony security wrap to hold it in place." (P5). In addition, BP is measured periodically using a cuff or, in some acute cases, continuously via an arterial line:

... if you have them on automatic blood pressures, then their blood pressure [is measured too]. You can also have them hooked up to their umbilical artery line to get their arterial pressure also.... You have the [blood pressure] cuff on the infant and it stays on there and then it'll just go off [take a measurement] as you set it [for the time interval you set it to] and I think the most frequent I've done is every 15 minutes. (P6)

Unless otherwise specified, for the rest of the paper, we collectively refer to all the continuous and instantaneous measurements as *vital signs*.

All these signals can be observed on a patient monitor screen next to the baby's bed. Figure 1(b) shows a disconnected patient monitor, which shows space for both continuous waveforms and discrete measurements. Babies who are born before 26 weeks are typically kept in a temperature-

and humidity-controlled incubator (see Figure 1(a)) and are only instrumented with a pulse oximeter and temperature probe because their skin is too sensitive for the EKG sensors. Such babies are usually interacted with minimally by the nurses: *"Honestly, the best policy with a baby that small is not to touch them at all. So you're really managing everything around them without hands-on touching them."* (P4).

Further, the patient monitor in a room is programmed by setting the lower and upper thresholds of the *acceptable range* for each of the vital signs. So when a baby's vital sign leaves the acceptable range, the patient monitor produces a warning in the room via an **alarm**. The alarm produces an *audible sound* and a *visible notification* on the screen of the patient monitor that shows the value of the vital sign that is outside the acceptable range. It is possible to pause the alarm function for a short period of time by pressing the alarm silence button on the patient monitor: *"You can pause it for 45 seconds or two minutes but then if you're in there for half an hour, you have to re-pause it every two minutes. So then eventually it kicks back on. There's no way to silence it for the whole time that you're in the room unless you turn it off - but I wouldn't want to turn it off because I would want to know if they're actually de-sating."* (P1). Most alarms are generated based on the baby's HR, SPO₂, and RespR values. Out of these, only the HR and SPO₂ values are clinically relevant to the nurses. The respiration waveform and resulting RespR values are highly noisy and are ignored by the nurses with respect to making decisions about the babies' state:

The respiratory monitoring on this EKG is useless, in my opinion. I don't think it works very well at all.... So if you're in the room and it's saying the baby's apneic [not breathing], well the baby's not apneic. His heart rate's fine, his oxygen is fine. It's just not picking up. That is super annoying. I wish I could just get rid of that whole thing [the respiration sensing and associated alarm]. (P4)

In fact, the alarm generated based on RespR signals has a different audible sound and is at a lower volume than the HR and SPO₂ alarms: *"[The RespR alarm] is a different tone and lower volume than the other alarms"* (P4).

Since the nurses take care of multiple babies at a time, each alarm generated at the patient monitor for a baby is sent to the associated nurse via a corresponding **alert** on a *phone* that they carry with them at all times. This phone is small, portable, has both a screen and physical buttons, and looks like a feature phone³:

So at [our hospital], we have phones. So those are hooked up to the monitor and if it goes above or... below the range, then it'll ring to your phone, kind of like a page, and then you can go into the room and see what's going on. So for heart rate, if it's lower, it'll ring to your phone. I don't think it rings to your phone if it's higher and then for oxygen sat, it rings to your phone based on your parameters. For oxygen sat, it rings both high and low. (P1)

The alert on the phone produces an audible sound and displays the *context of the alarm*, i.e., the room of the alarm and the vital sign value that caused the alarm: *"... so I'll*

hear it going off and I'll take a look at it and it shows you, I see what room it is and what the value is." (P6). Only the SPO₂ and HR alarms are sent to the phone to produce alerts.

When an alert is sent to this phone, the nurse has the option of accepting, rejecting, or ignoring the alert. The nurse can **accept an alert** by pressing a dedicated accept button on the phone. Accepting an alert signifies that the nurse accepts responsibility for that alert (and the alarm that triggered it). Accepting an alert on the phone stops the audiovisual alarm on the patient monitor in the baby's room as well as the audiovisual alert on the phone. Similarly, the nurse can **reject an alert** by pressing a dedicated reject button on the phone. Rejecting an alert signifies that the nurse cannot accept responsibility for that alert (and the alarm that triggered it) at that moment. The nurse can also reject an alert by ignoring it (i.e., not pressing the accept or reject button on the phone). In such cases, the alert will time out and then ring again after a short interval. If the nurse ignores it a second time, the system considers it a rejected alert (more on this later).

In addition to receiving alerts, the other use of the phone is to get updates about things happening in the NICU as well as to call others to coordinate care for the babies, including with parents:

... they will send us text updates on things that are happening in the unit, updates on what might be going on or a lot of times it's like someone's looking for equipment.... I use it to call the nurses, parents can use it to call me, doctors can use it to call me, and I can use it to call the doctors. We don't use a pager or anything; we just call our doctors directly. So if I need help from the charge nurse, the admission nurse, I would just call. (P4)

In this paper whenever we mention the phone we mean this NICU phone and not any personal device that the nurses may also have.

4.3. Nurse buddies

If an alert is rejected by a nurse either by pressing the reject button on the phone or by ignoring the alert twice, the alert still needs attention. All rejected alerts are sent to another nurse in the neighborhood designated as the "buddy" of the nurse who rejected the alert:

So say I'm in the middle of a diaper change and I can't touch my phone, I have a couple of seconds. It'll send it to my phone, I have a couple of seconds to press accept or reject. If I don't, it'll send it again. Then I have a couple of seconds on the second one and if I don't press anything, it's going to assume I'm rejecting. Once I reject it, whether I press reject or just don't answer it, it will go to my, what we call a buddy. (P4)

A "buddy" is a backup nurse. Every nurse is designated as a buddy for someone else in the neighborhood at the beginning of every shift: *"First thing in the morning, we set up our phones, we have a buddy."* (P2). If the buddy also rejects or ignores the alert (because they are busy), the alert goes to all the nurses in the neighborhood at the same time: *"... and then if that buddy's busy doing something, it goes to*

the entire neighborhood." (P2), which is meant to ensure that someone attends to the baby producing the alarm.

4.4. Alarms and alarm fatigue in the NICU

Alarms produced at the patient monitor in a NICU can be one of three kinds: (1) *legitimate*, which indicates that the baby's health has deteriorated; (2) *false*, where the alarm was generated erroneously and the baby's condition has not deteriorated; and (3) *non-actionable*, where the alarm is genuine in the moment but the baby's vital sign quickly came back into the acceptable range. All alarms are generated based on one or more of the instantaneous vital signs (e.g., SPO₂ and HR) crossing a predetermined threshold.

Legitimate alarms are self-explanatory and the main purpose of having the alarm system. False alarms are frequent in the NICU and come from a variety of sources, such as:

- Motion artifacts from kicking and other baby movements: *"The most common false alarm we get is the baby just kicking their foot around. They're kicking their foot or you have it on their hand and they're waving at you from the hallway and then the sensor is not picking up but they're just moving around. They look absolutely fine."* (P1)
- Sensors stuck to another surface/person while moving the baby around: *"especially when they do skin-to-skin with the baby, you go to put the baby back and you realize that 'Oh my gosh, this monitor has been just beeping off and it doesn't look like a good signal' and then you go to take the baby off and one of the [sensors] is stuck to mom's shirt or to her chest."* (P2)
- Poorly wrapped and dirty [sensors], which have not been replaced for a while: *"So the pulse ox could be wrapped either too tight or not tight enough around the foot or the hand. The actual pulse ox itself could be just really dirty and not picking up properly: it just needs a new one."* (P6)
- Medical procedures: *"... when there's someone from the lab like drawing blood - where they draw blood from the babies, they do heel sticks and that's a lot of times where your pulse ox is. So as they're drawing blood, all of a sudden it's showing that my oxygen sat is like ten and I walk in there and the baby's pink as can be and they're just mucking around with the baby's foot."* (P2).

Finally, non-actionable alarms are produced when one (or more) of the baby's instantaneous vital signs is hovering around the alarm threshold such that every time the baby's vitals dip below (or above) the set threshold, an alarm is produced but before the nurse can react to it, the baby's vital sign corrects itself. Non-actionable alarms are extremely common in the NICU, given the physiology of the preterm baby:

... sometimes when babies are premature, you know, they have a lot of variability in their saturation. So this baby, her limit was set at 88 to 95 for, that's where we want her goal saturations but sometimes if they take a couple of shallow breaths or hold their breath for a few seconds, their saturation will dip and then

they'll sort of take a couple of breaths and it will come back on its own with no intervention from me. My phone doesn't know that I don't need to intervene. So, say she's set at 88 and her sat drops to 87, I'll get a message. She takes a couple of breaths, her sat comes to 90 and then she does this whole thing. Like sometimes these babies can do this, you know, once every 3 minutes, 2 minutes - oh yeah, so I mean I counted one day and in a two-hour span I got, I stopped counting at 120 alarms for ... I think I got about 90 minutes in and most of them are alarms you do not have to intervene on. (P3)

As with any ICU, the presence of a large number of false and non-actionable alarms has resulted in almost all nurses stating that they have *alarm fatigue*: *"So you get... I think you call it alarm fatigue, it's just - especially if you have babies that are really the type of baby that has a lot of desats or a drop in their heart rate or whatever. Sometimes it could be a constant beep, beep, beep, beep and you have to accept or reject or whatever and it's constant."* (P2), which is not surprising and is a known phenomenon in nursing, especially in intensive care units (Tanner, 2013). One participant put it: *"... if you probably ask any NICU nurse, their biggest thing they'd like to see change is the frequency of alarms; and alarm fatigue is real..."* (P3).

4.5. Typical care-time duties for NICU nurses

A nurse's duties for a given baby includes taking care of the baby's needs during *care-time*, which happens around every three to four hours around the clock: *"Care-time is pretty much every time that they need to eat. So typically for our babies every 3 hours, we call them care-time and that is when you need to be in there with the babies"* (P6). The following is a summary of the activities in the NICU where our participants work that nurses perform during *typical care-time* (this is not an exhaustive list): (1) the nurses perform a full-body physical examination of the baby: *"... depending on what that baby is up to, we're doing a full head-to-toe neurological, respiratory, cardiovascular, skin, GI [gastrointestinal], a whole full head-to-toe assessment on them"* (P3); (2) the nurses check the baby's vital signs, change diapers, and reposition the baby⁴: *"So you're going in there, you're doing your assessment, getting their vital signs, changing their diaper, feeding them, and then repositioning them, and then you ideally leave them alone for the three hours in-between."* (P6); (3) the nurses are required to enter the baby's status information (e.g., instantaneous vital signs, pain assessment, feedings, intakes and outputs) into the EHR, which is also used as a way for the system to track the work they are doing: *"So we listen to them with the stethoscope, manually measure their instantaneous vital signs, manually rather than just relying on the monitor all the time.... So like whatever you have in the chart, if something were to happen, if you didn't document it, you didn't do it."* (P1); (4) feed the baby and take care of their medication: *"A lot of our babies at [our hospital] are feeder-growers, as we call them. So they're just there because they're not taking enough feeds on their own, so they can't go home yet. So we'll have the nasogastric tube to support that."* (P1); (5) check the feeding tubes, various IV [intravenous] lines and sites, and infusion pumps

connected to the baby: “So we’re constantly doing our rounds every hour, checking our IV pumps every hour, checking our respiratory settings, devices every hour.” (P7); and (6) involving the parents in the baby’s care: “If the parents are there, you try to get them involved in [the baby’s care].” (P1)

4.6. Interacting with parents

One of the most important and unique duties that falls on the nurses in a NICU is that of interacting with the babies’ parents. The NICU where our participants work implements family-centered care practices (Gilstrap, 2021). That is, parents are an integral part of the baby’s care in the NICU and have an unrestricted presence in the NICU. Typically, the role of the nurse toward the parent is five-fold:

Status update: Providing the parents with updates on the baby’s health status when they visit the baby:

So when the parent comes in... it’s usually the nurse’s responsibility to up[date] them, like: What changes have we made for the day? What’s going on? How are they doing? What are we planning to do for the next 24 hours, overnight? What are we doing for them going forward? (P1)

Teaching: Teaching the parents how to care for their baby as much as possible, including feeding the baby, safe sleep, diaper changes, touches the baby likes, handling any medical equipment present, taking their temperature, etc. – especially as the babies get closer to going home:

[The] teaching starts when they get into the NICU but teaching them how to change a diaper on your baby that weighs a pound and 4 ounces is very different than changing a diaper on a 9-pound baby, you know. How to, I’m teaching them what type of touch the baby likes, how to take the temperature, what things they can do for their baby to help that baby... it’s okay to read to your baby who weighs less than 2 pounds, the baby will still hear you, it’ll still help their development. And then as the baby gets older, teaching them how to feed the baby, teaching them how to, what signs to look for - because we have monitors [in the NICU], babies don’t go home on monitors - so, like what signs to look for if the baby did have some sort of an event where they choked and some time maybe their heart rate dropped or the sat dropped, what to look for, for that. As they get even closer to going home it’s, a lot of it can be just teaching them how to properly - our babies go home generally on added calories - so if they go home on breast milk alone, you know, you express breast milk, we’re adding formula powder into it to make the caloric intake higher to help them grow because they were born premature. So teaching them the right amount of powder to add to the certain amount of [milk], teaching them about safe sleep, teaching them about, if they’re going home on any medical equipment, how to use that equipment.... (P3)

Involve parents in care: Involving the parents in the day-to-day care of the baby (especially changing diapers and taking their temperature), provided the baby is stable and the parents are comfortable:

... but if the baby’s really small and has a lot of wires and like if they have the UAC [umbilical arterial catheter], which is the [tube] in their belly button that monitors their blood pressure, that’s the one in their artery. If they have that one, chances are I probably wouldn’t let the parent change the diaper if they’re super nervous. If they’re good and like some parents are better than others. If they’re really good, it might be okay but if

they’re kind of not as comfortable and not as confident, I wouldn’t let them do it because... I don’t want to risk their nervousness pulling something out that is keeping this baby alive. (P1)

Kangaroo care: Facilitate kangaroo care (skin-to-skin sessions) between the parents and the baby if the baby is stable and doesn’t have interventions that might get in the way:

If a baby is stable off of a ventilator and does not require a humidified bed to stay warm, we usually offer [kangaroo care] to [the parents] once a day, depending on the age and status of baby. We also hesitate to offer skin-to-skin for babies who have an umbilical IV line but have done it in some circumstances. If a baby only requires a nasal canula or no oxygen at all, there is no limit to when the baby can be skin-to-skin. (P5)

Kangaroo care is done by placing the baby on the parent’s bare chest: “The baby is placed with his/her chest facing the [parents]. We try to expose as much skin to the parents as possible.” (P3).

Emotional support: Since having a baby in the NICU is a very tense and anxious situation for the parents, the nurses also play a vital role in managing the parents’ emotional needs: “I mean, we’re their psychiatrist, their psychologist. You get to know families pretty well.” (P3). Nurses are also a source of advice for the parents to deal with their situation: “So when so when things are hard, they do look up to you for advice even after they’ve talked to the doctor, they always want your input because you know their baby best. So yeah, we support them through some of the harder times too.” (P5).

5. Study findings 1: All elements of the monitoring technologies impede the nurses’ ability to perform their duties in some way

We began by asking the participants about the challenges NICU nurses encounter when using monitoring technologies. We found that extant monitoring technologies in a NICU often impede the nurses’ ability to perform their duties. We identified six main themes in this regard, which we describe next (summarized in Table 3).

5.1. Wired vital-sign monitoring disrupts a variety of NICU workflows

Vital-sign monitoring in the NICU (EKG, plethysmogram, etc.) is wired and involves sensors on the baby’s body sending their measurements through a wire/cord to the patient monitor to be processed and displayed in real time. However, the presence of the wires imposes considerable complications for the nurses in carrying out their duties. These complications broadly come in five forms:

It disrupts care-time activities for the nurses: The wires get in the way of the nurses’ duties and care of the babies:

... then just all the wires, it’s everywhere in the bed if the baby’s so small. Just doing their diaper, you’re moving all the wires out of the way, trying not to tug on anything. Or if you’re changing the blankets and you have all of these wires, sometimes it’s just so much to then - you don’t want to accidentally pull on anything and pull it out, so then you have to get somebody to help you just change a simple blanket. So

Table 3. A summary of the various ways in which the monitoring technologies impede the nurses' ability to perform their duties in a NICU.

The wired sensors disrupt a variety of NICU workflows	<p>The wires get in the way of the nurses' care-time tasks</p> <p>The wires make it difficult for the parents to interact with their baby</p> <p>The wires make kangaroo care difficult both for the nurses and parents</p> <p>The wires are a tripping hazard</p> <p>The ubiquity and intrusiveness of the wires causes the parents to disconnect them when interacting with the baby, thus causing false alarms and needlessly increasing the nurses' workload</p>
The design of the patient monitor is insufficient to meet the nurses' needs, especially in a high-workload setting	<p>The patient monitors are only designed to display two babies' vital signs in real time</p> <p>An event-based alarm system (e.g., Alarm watch) does not compensate for the inability to track more than two babies at a time</p>
The high stakes of handling phone-based alerts can cause the nurses considerable frustration	<p>The requirement for nurses to interact with every alert on the phone forces them sometimes to do so blindly</p> <p>Several nurses expressed considerable frustration with the near constant need to interact with the phone</p>
The false alarms produced from the nurses' interaction with the babies cause frustration	<p>Most nurses go to great lengths to accept alerts on the phone even when their hands are full, such as using their elbow or chin</p> <p>Some nurses ignore the alarms generated from their interaction with the baby, causing their colleagues extra work and frustration</p>
The frequent alarm sounds negatively impact the babies, nurses, and parents	<p>The frequent alarm sounds stress the babies</p> <p>The frequent alarms can cause the parents severe anxiety</p> <p>The alarms sounds can be too loud, even for the nurses</p>
The setup of the monitoring technologies leads parents to interfere with the nurses' duties	<p>Parents often ask the nurses not to monitor other babies on the patient monitor to avoid hearing the alarms from other babies, which prevents the nurses from monitoring their other babies</p> <p>Some parents turn off the alarm on the patient monitor because the sound bothers them</p> <p>Parents often inadvertently hover near the patient monitor, which prevents the nurse from accessing it</p>

somebody can hold the baby up and then you can switch the blanket out from underneath them. (P1)

It disrupts family-centered care: The NICU where our participants work implements family-centered care, which, among other things, is about involving parents in the care of their babies in the NICU (Griffin, 2006). The wires make this hard to do, as the parents often hesitate to interact with the "wired" babies, such as when they are asked to change the baby's diaper or do a feeding:

You know, a first-time parent, it's tough for them because, even changing the diaper. The sensors are there, the wires and they're just like, 'uh, I can't maneuver around it.' So we do our best to show them how to do it. We do our best to kind of like walk them through it and assist them in any way we can, whether it's just holding the legs up or holding the wires together so that they're not.... I mean, as a first time parent, it's already scary enough to change the baby's diaper. (P7)

It disrupts kangaroo care: Kangaroo care becomes especially hard to do with the parent and is not always even feasible, despite the great extent of its positive benefits: "[Kangaroo care is] very cumbersome. It's very good for the baby but the reality is it's very difficult to get the baby out of the bed when they have all of this stuff.... It can be a good 10 to 15 minutes to get the baby out of the bed." (P1).

It becomes a tripping hazard: The wires are a tripping hazard, especially for the nurses: "I have actually had an injury at work where I tripped on [a wire], which luckily didn't hurt the baby but [the sensor] ripped right off of her and I hurt my knee. They're just, the wires are horrible. The wires are worse than the monitors themselves." (P4).

It can provoke potentially dangerous actions from the parents: The presence and cumbersome nature of the wires causes some parents to knowingly disconnect the sensors,

for instance, to put an outfit on the baby. This can cause unnecessary anxiety for the nurses who have to investigate the resulting false alarms, which also likely pulls the nurses away from their duties:

Sometimes the parents will pick up the baby on their own in the room and next thing we know - or they'll actually disconnect a [sensor] to like fit the baby's leg into an outfit or something and then you go running in there and they're like, 'Oh, I'm sorry. I just unplugged it for a second.' (P2)

Some of these issues (especially those related to the negative effects of wired sensors on parent-baby bonding) have been discussed in prior work conducted in a European hospital half a decade ago (Bonner et al., 2017). The fact that these issues around wired sensors persist indicates that things are slow to change in a hospital setting and that the problems presented here can be generalizable outside of the US context.

5.2. The design of the extant patient monitors makes baby monitoring more difficult for the nurses

It is often necessary for the nurses to know the status of all the babies in their care at all times. However, the individual-room layout of the NICU necessarily prevents the nurses from being able to keep all their assigned babies in constant visual contact. Consequently, they have to rely on the patient monitors: "Honestly, you can't [have eyes on all of your patients all the time] when you have four [babies assigned to you]. That's the real answer, you can't. You have to rely on the monitor... because you can't have eyes on them all the time." (P1). The extant patient monitors are

only designed to allow nurses to monitor, in real time, at most two babies at a time:

... you can also bring up the vital signs of another patient into a different room. So you can watch another baby's heart rate and you can do all [the signals] if you want but usually we will just bring up the heart rate and oxygen saturation of another baby into whatever room that you're in. (P6)

Often the nurses have to decide which two babies to monitor in real time, based on how acute their condition is:

If I'm sitting [at] my station, my computer station or whatnot, there we have like a plexiglass window in the babies' rooms but what I try to do and what we all try to do is sit near your most critically ill baby. Okay, so you actually have a visual, whenever you're documenting or whatever, on that baby and then what I'll do is I'll put my other baby underneath that monitor. So even if I was documenting outside of the room and I'm in the hallway, I can still see, 'ooh my little baby Smith just dropped down to 75 but, boom, already bounced back up to 90.' Then I can accept my phone and I know that that baby is safe. (P2)

That being said, the monitors do allow for an event-based feature, called Alarm Watch, which displays the alarm conditions of as many babies as they want: *"If you pick Alarm Watch, you can set all four of your babies to it and then it'll pop up on the bottom but only if one of their parameters goes like above or below, then it pops up with whatever alarm it is."* (P1). Nurses use this feature to let them know, while they are in a baby's room, if any of their other babies are alarming: *"... we do Alarm Watch. So let's say I'm in one room specifically, I can put the three [other] babies and I can program it to alarm me if there are any abnormalities with these three other babies."* (P7). However, the Alarm Watch feature is not a good substitute for continuously monitoring all the babies' waveforms: *"I wish that you could pull up all four of your babies all at once and not either two or just [Alarm Watch]..."* (P1). Further, as the number of babies that a nurse needs to care for increases, the probability of multiple babies alarming at the same time goes up. However, the design of the Alarm Watch feature does not handle such situations effectively:

So if I have two or three other patients, when the Alarm Watch pops up, I'm watching [it] and then if another baby alarms, [the previous Alarm Watch pop-up] goes away and now I can only see the new alarm. Well if the new alarm was like a respiratory rate that doesn't matter but I was actually watching the kid to see if I needed to get up and go see him (P4)

5.3. The large number of phone-based alerts and the high stakes for handling them can cause considerable frustration for the nurses

Given the large number of false and non-actionable alarms produced by the patient monitor in the NICU, the nurses are bombarded with alert notifications on their phones that require immediate action vis-à-vis the phone even if they are otherwise busy. Further, the number of alerts received is exacerbated by the nurses also receiving their buddy's alerts. The sheer volume of alerts thus received by the nurses often forces them to accept alerts without looking at their phone: *"I've hit the button a hundred times in the past two hours*

and I'm just, at this point I hear it and I hit accept and then I'm like, 'Oh, I didn't look at that.' So then you get up and look at all the babies in the hallway." (P3). However, this need to continuously accept alerts forces the nurses into one of two anxiety-provoking situations: (1) accepting an alert on the phone and not knowing if that alert was for a baby assigned to them (whose state they know) or one forwarded from their buddy: *"So then sometimes you accept it because you think it's your baby and then you're like, 'oh, shoot! Was that even my patient I just accepted?'"* (P1); and (2) accepting an alert on the phone for one baby while thinking the alert is for another baby whose vital signs the nurse is currently viewing on a patient monitor, which happens because of the number of babies assigned to the nurse and the constant context-switching they need to do to deal with the voluminous alerts received:

Sometimes I don't even look at my phone because I see it on the monitor, which is dangerous because that could be a different alarm So sometimes I'll accept it and I'm like, 'Ugh, now I don't even know what I accepted.' Now I've got to run out into the hallway and make sure everyone's okay because I don't even know what I accepted. (P4)

Not surprisingly, several nurses expressed considerable frustration with the constant need to interact with the phone: *"There are just so many times where us nurses are like, 'I just want to throw this phone!' Yeah, it gets, obviously, a lot for us."* (P7). One participant even added to that by stating that they did not need the phone at all for their work, based on their prior experience in the NICU:

I would say in an overwhelming majority of them, you don't need to intervene Or I have the monitor on so I can see what the other patient is doing. I don't really need the phone at that moment We've had times where we've had sort of downtime or where they were upgrading phones and we didn't have them. We had an instance where we got hacked and our system was down for a while and we didn't have the phones and I don't think there were any adverse events. I think the phones are a little unnecessary. (P3)

5.4. Dealing with false alarms caused by the nurses' interaction with the babies is extremely frustrating

False alarms are often produced as a result of care-time, when the nurses are taking care of the baby in person. These alarms cause considerable frustration for the nurses because they are still expected to accept the corresponding alerts (via the phone) even though they are in the room with the patient monitor that is producing the alarm: *"... it's like, 'I'm in the room, why is this [alert] going off? I'm right here.' but I still have to do the thing to my phone, go over and silence it. So that's annoying when you're in the room."* (P4). To be able to do their job in the midst of this need to accept all alerts, the nurses use any means necessary to press the accept button on the phone, even when their hands are full, to prevent the alert from going to their buddy:

I know exactly where my accept and my reject buttons are, even though [the phone is] not in my hand. So if I have my hands in the bed or I'm feeding the baby, it's amazing what I can do to

accept an alert while I'm still feeding the baby. I use my chin or, you know, I try to use my elbow. You become quite creative after a little while.... (P2)

The nurses have the option of temporarily silencing the alarms for the baby in whose room they are located, which prevents corresponding alerts from being sent to their phone. However, this silencing has a very short time-out duration of two minutes, which is often not enough for the nurse to perform all the care-time activities with the baby: "... you can only silence it for two minutes, which is supposed to be a safety mechanism so that if something happened and you stepped out of the room, at least it would come back on in two minutes but when you're in the room, it gets annoying." (P1). Another option that the nurses have is to suspend the alarm when they are interacting with the baby. Suspending the alarm stops the alarms for good until the alarms are turned back on. For obvious safety reasons, this option is only used sparingly:

Yes, so there is an option on the monitor in the room to... suspend [the alarms] but if you do that, then the monitor won't pick up what the baby's doing. So if they do have an episode while you're in the room, you're not going to know how low they went because it's not going to go up on the monitor. Sometimes I do [use it], yes. If the baby can be trusted for a short amount of time, I will but if it's a baby that is, like I said, really critical, no I won't do that on that baby. (P6)

Another complicating factor is that some nurses just ignore alerts produced when they are interacting with a baby. Ignoring such alerts exacerbates the number of alerts received by buddy nurses who now have to run around to see if these alarms are real, thus complicating and adding unnecessary stress to the nurses in performing their duties:

... you have nurses, you have older nurses who just completely ignore their alarms, don't respond to them. I mean, they may be in the room with the baby where it's happening but they don't respond to the phone part of it and they think because they're in the room, I'm here, everything's fine, they don't accept [the alert] and so it goes to everybody else in the neighborhood. So there are certain nurses where you constantly just get their [alerts] throughout your shift and it's pretty annoying but the other side of that is you can't just assume that that nurse is in that room. I would have to stop what I'm doing, put a baby back to bed, walk down the hall, check on that alarm, accept [the alert] or decline it, walk back to my room, go back to my patient, pick my baby back up, start feeding that baby again or whatever I was doing. (P5)

5.5. The frequent alarm sounds negatively stimulate the babies, their parents, and the nurses

Each alarm in the NICU results in an audible sound at the patient monitor where it is generated. Alarms are also produced when a nurse sets up a second baby on the patient monitor or setup Alarm Watch. Along with the excessive rate of false and non-actionable alarms, alarms from other babies on the patient monitor can produce a near-steady stream of alarm sounds, which creates a stressful environment for the babies in the NICU, who are already in a precarious situation: "... it's just a lot. It's a lot for the day. It's a lot of noise. It's a lot of stimulation." (P4). A stressed baby's vital signs become erratic, which makes them require

additional care and attention from the nurses who already do not have time to spare: "... their vital signs and everything that we're monitoring is going to be all out of whack if they were stressed out for a bit." (P1).

Further, the constant presence of alarms negatively impacts the parents of the babies as well in that it can cause them undue anxiety in an already very hard situation: "there's like a certain group of parents who will obsess over them and be really upset and be hitting the call light like, 'the alarm went off and I'm like, 'I know! I know, I get it on my phone. I'm watching them in the other room. Everything was okay. I would come in if he needed....' All they know is that something wasn't right on the monitor even if I know it wasn't a big deal.'" (P4). Consequently, the nurses take time from their already busy schedule to educate the parents that not all alarms are actionable or even correct:

So obviously when they come in, we tell them... it'll alarm: these are the parameters. It will alarm for this reason, it will alarm for that. We like to let them know. We like to educate them on that. This is what it is when it's a false alarm. This can cause a false alarm, this can cause this and typically they understand it. They need reinforcement, obviously. You know, they'll just be like, 'what's the parameters that they should be at?' and I'll show them on the monitor, this is the parameters. So they get nervous when they hear it, especially when they're, when they start feeding the babies and then their oxygen level goes down. So that's when you just educate and you're like, listen, they're not feeding the baby as they should. 'Let's do it this way versus that way.' (P7)

The nurses have some ability to: change the alarm sound on the patient monitor, control the volume of the alarms on the patient monitor, and alter the sound and volume for the phone alerts: "We have limited ability to change alarm sounds but can change the volume on both the monitor and phone. They are mostly preset." (P4). However, the alarm sounds still negatively affect some of the nurses who stated that the sound of the alarms is often too loud for them: "I mean, again, I think it's very important to hear the sound because you kind of get in tune to what it sounds like for different things but if it could get quieter, that would be a beautiful thing." (P2).

5.6. The setup of the monitoring technologies is such that the parents end up interfering with the nurses' duties

The NICU is a unique medical setting where the nurses have to manage not only the needs of the baby but also cater to the parents of the baby as well:

Yeah, I worked with adults before this and families with adults are like a whole other animal but with babies, I feel like they are just so nervous and they just they just obviously want their babies to be okay. So whatever you say as the NICU nurse, they are just like, eat up all your words.... They just, they trust you. So I feel like you really have to value what you say to them because they're going to take it. They're going to take it all in and, like, what you say goes. So, the big thing is you can't give them false hope.... You have to always just like really know what you're saying to them. (P6)

Further, for obvious reasons, the parents of the babies are often incredibly anxious and stressed: "Just emotionally,

Table 4. A summary of how the nurses use their experience to cope with the challenges presented by the monitoring technologies in a NICU.

The nurses leverage their baby assignment to better monitor all of the babies in their care	When assigned babies in adjacent rooms, the nurses are able to monitor up to four babies simultaneously When assigned twins, who are in the same room and have one patient monitor each, the nurses can monitor up to four babies simultaneously
The nurses sanity-check the alarms as a way to cope with the high volume of false and non-actionable alarms	In the event of an alarm, the nurses need to check the waveform (which they can only view on a patient monitor) This sanity-checking of the alarms is necessary for both false and non-actionable alarms
The nurses use their experience to make dealing with the alarms as unobtrusive as possible to their current tasks	Nurses use their experience and knowledge of the baby to determine how and when to act in the event of an alarm In certain cases the nurses are able to tweak the alarm thresholds, in consultation with the physicians, to reduce the non-actionable alarms
Given an increased workload, the monitoring technologies' design has led NICU nurses to work more independently	The nurses expressed considerable pride in doing their utmost to handle the voluminous alerts The nurses who do not actively manage their alerts create friction in the group Despite the isolating effects of their high workload, the nurses still think of themselves as part of a team

they're very stressed out. They always can call the NICU anytime they want for updates. So sometimes the parents will call every other hour for an update on their baby, which is fine and they can but then by the end of the night you're like, 'Still, nothing has changed.... It's going to be weeks until they get better.'" (P1). A side effect of having parents near the monitors is that they sometimes interfere, often inadvertently, with the monitoring technologies and thus adversely affect the nurses' workflow.

As we have seen, being able to monitor multiple babies simultaneously helps the nurses manage the babies in their care. However the babies' parents often ask them to disable the monitoring of other babies in any form: "[The parents] usually complain and have us take it off because then it alarms, it makes the audio sound for the parents every time someone else's baby's alarming if it's set to that monitor.... So if the parents are there, we'll shut it off but then you really don't see what's going on." (P1). Further, some parents even turn off alarms because the sound bothers them even though this leaves the nurses unaware of the baby's state: "Some parents have actually touched the monitor and shut the alarm off, have silenced it. We have to tell them not to touch the monitor... just because they didn't want to hear it alarming.... [The parent] will say, 'I couldn't listen to that, so I had to silence it.'" (P5). Finally, some parents physically block access to the baby's bed or the patient monitor: "You get hoverers, so they're just hovering over the bed and sometimes you kind of have to be like, 'I've just got to, I've got to do this,' you know but it's not... I get it, it's their baby. I would be the same way." (P4).

6. Study findings 2: When possible, the nurses use their experience to compensate for the challenges presented by the monitoring technologies

Next, we asked the participants how they overcame for the challenges presented by the monitoring technologies. We found that they use their experience in interesting ways to overcome the limitations presented by the monitoring technologies and that this is only feasible in some situations. We identified four main themes in this regard, which we describe next (summarized in Table 4).

6.1. The nurses leverage their baby assignment to better monitor all of the babies in their care

The patient monitoring system available at the NICU seems to be designed with the assumption that nurses have a two-baby assignment. As mentioned before, this two-baby limitation of the monitoring technologies prevents the nurses from keeping track of all the babies under their care when their workload is high. One workaround is that nurses often take advantage of the location of the rooms of their assigned babies to monitor all of their vital signs in real time:

I'll be sitting in a desk and there's a room to my left, a room to my right. So if I have four babies, I have two monitors currently that I'm, that I get to look at. So I'll have half the monitor on each to one baby and half the other monitor on a second, on the second and fourth baby, if you will. (P7)

Another nurse stated that they liked taking care of twins for the exact same reason, since both twins are usually placed in the same room and each baby has its own patient monitor, which allows the nurses to continuously monitor all four babies assigned to them: "I actually like taking care of twins because then I'll be in the twin room and I'll have the two twins and then I can have two other babies underneath because they have two separate monitors. I'd rather just watch them than have the Alarm Watch but the only way to watch three babies at a time [when not taking care of twins or when you can't arrange a common vantage point for two babies in adjoining rooms] is to have Alarm Watch" (P4).

6.2. The nurses sanity-check the alarms as a way to cope with the high volume of false and non-actionable alarms

As stated in Subsection 4.4, most of the alarms in the NICU are false or non-actionable. However, every alarm has to be checked to make sure it is not something that requires urgent action. Therefore if an alarm sounds, the nurse needs to make sure the alarm is not false by checking the baby's EKG or PG waveform by one of two means: (1) by viewing the alarming baby's patient monitor either by going to the alarming baby's room or by looking through a window into that room: "The rooms have windows from the hallway, so

half the time you can just walk by the room from the hallway, see the monitor, and then if it looks... if the strip looks crazy, then I would just know that the [sensor] wasn't stuck on them well." (P1) or (2) by pulling it up on the patient monitor of the room they are in (as the second baby on that monitor, which shows up at the bottom of the screen):

The monitor will say all these wacky numbers ..., that's not actually correct but that's what the monitor thinks because it's not picking up on the baby.... That's another time where we will look at the actual waveform because it won't be correct. It won't be a normal waveform. (P6)

The NICU alarms follow a very simple rule, where an alarm is generated every time the measured value is outside the pre-determined acceptable range for that vital sign. Unfortunately, the monitoring system does not provide the corresponding, often more important piece of information, that the vital sign in question has returned to the predetermined acceptable range. For babies in the NICU, the dip below (or above) the threshold of the vital sign and back again is often very quick, thus making this a non-actionable alarm. Therefore, sanity-checking the alarms works just as well and is necessary for the non-actionable alarms as it is for false alarms:

... we get a message saying, okay, your baby's sat is less than the [lower] parameter. We don't get another message saying it went back up. So all I know is the baby went down. I don't know what happened after that. So it can go from, say the sat limit is, the lower limit is 90. I can get an [alert] saying it's 85 but it will not tell me anything below that. So it could be 40 when I get in the room or it could be 100 but if I could see it on the monitor, if I could see multiple patients on the monitor at a time, that would be helpful.... So all the alarms we get, it doesn't tell us that the baby goes back into normal range. It just tells us that at one point in time, the baby came out of normal range. That's all it tells us. (P3)

6.3. The nurses use their experience to make dealing with alarms as unobtrusive as possible

We found that nurses developed a sense for when to intervene for alarms and found ways to make dealing with the alarms as unobtrusive to their work as possible. Some participants stated that they believe the alarm sounds are different enough for them to recognize them individually:

It takes a little bit, you just have to, it'll take you a little while to sort of distinguish which sound is which but after a while, you do, you know. If you played me each of the sounds, for example without actually physically showing me a monitor, I can tell you what it meant. (P3)

In fact, through their experience working at the NICU, the nurses developed a sense for the state of the baby, based on the alarm sound patterns without having to check on the baby:

... some alarms, you hear them and you know it's bad. So if the baby's heart rate and oxygen drop at the same time, that is a bad alarm. A lot of times you'll get an alarm [or alert on the phone] ... and then it's a question of does a second one happen right away and that's how you know that two are dropping at the same time. (P4)

If the nurses are busy and they determine that an alarm for a baby they are not currently with is false, they do not

immediately attend to the alarming baby but rather prioritize their current task: "[The alarms] are very sensitive. So the way I handle it is I'll look at the waveform and I'll ignore [the alarm], honestly the first time, like, the baby's fine, the baby's great, the waveform is off or, like, no, it's fine. If it keeps doing it, then I'll go in and I'll assess." (P7). For non-actionable alarms, the nurses sometimes take an interesting approach, often in consultation with the physician. If a baby is hovering around the upper threshold of a vital sign range, they might increase the *upper* threshold to reduce the alarms:

In this situation, I will bump the baby up for oxygen and the respiratory device, I'll bump it up and I'll increase its parameters, which I'm not supposed to do but we do have babies who we call very swoony. Just like that, they'll go up and down, up and down, like, there's no happy place for them. So that's when - and again, it becomes a lot for us - so we do up the parameters so that we don't hear it. So if they're supposed to be at 95 and they're constantly fluctuating between 95 and 97, I'll bump them up to 98 and then at the end of my shift, put it back. (P7)

However, this is only done on the upper end of the threshold and not on the lower end because that can be dangerous for the babies: "On the lower side... if [the baby is] supposed to be at 90 [SPO₂] and he's like 89, 88, I wouldn't [change the threshold]." (P7).

Our findings in this regard match the observation in a previous study from two decades ago (Bitan et al., 2004), which indicates both how little things have changed in terms of reducing false and non-actionable alarms in a NICU setting and how the nurses need to be adept to deal with this problem.

6.4. In the context of an increased workload, the design of the monitoring technologies seems to have led NICU nurses to work more independently

Nursing in a NICU is generally a cooperative activity. However, the increased workload, in terms of the number of babies assigned to each nurse, has created an environment where the nurses are forced to work as independently as possible. One of the participants, who previously had worked at a different NICU with only two-baby assignments, stated how having fewer babies assigned to them allowed the nurses the space to work more cooperatively:

I'd say we interacted and helped each other out a lot more at [another NICU] than we do at [this NICU] but at [the other NICU], we were a lot less busy. There we only did one- or two-baby assignments and that was the cutoff. You couldn't get more than them but at [this NICU], where we have three or four, you're so busy that you're just trying to get your own stuff done that if somebody else needs help, you almost don't even have time to help them because you could use help yourself trying to finish everything that you need to do. (P1)

This trend toward working independently with a higher workload is compounded by the need to accept alerts on the phone, which further increases their workload. For instance, despite the large number of phone alerts each nurse has to handle, the nurses expressed a considerable degree of pride

in doing their utmost to handle their own alerts and not let them go to their buddy, out of respect for how busy their buddies are: “of course, you... want to... try really hard to accept your [alert] and not have your neighbor, your buddy, get it all the time because, again, they have enough of their own to get. They don’t really need to hear yours.... I try to pride myself in answering my own [alerts].” (P2). Furthermore, when nurses do not actively manage their alerts and let them spill over to their colleagues, it creates friction in the group: “You can get frustrated, especially if, say you have a coworker in the hallway who’s not great about answering the phone, so then you’re getting your own [alerts], you’re also getting her [alerts] and I have gotten a little snippy with people because it’s just so frustrating.” (P4)

Despite the aforementioned isolating effects of their high workload, the nurses still think of themselves as part of a team, as evidenced by their: (1) developing and fostering a culture where each nurse considers all the babies in the hallway to be their responsibility: “If they’re on break or they’re busy or whatever, if they’re in the bathroom, God forbid, you’re responsible for those babies. We kind of consider ourselves responsible for everyone in the hallway. Like, you just do because that’s who we are.” (P4); and (2) actively trying to be aware of the status of all the babies in their neighborhood: “... if the door’s shut, you can hear [an alarm from the patient monitor] but it kind of sounds like it’s in another hallway almost. So we don’t like to shut our doors often because we like to be aware of everything that’s going on [and] if the door’s open, you can definitely hear it.” (P4).

7. Study findings 3: The nurses felt that all elements of the monitoring technologies needed improvement

Finally, we asked the participants about any improvements to the monitoring technologies they would suggest. We identified four main themes in this regard, which we describe next (summarized in Table 5).

7.1. The nurses wanted vital sign monitoring in the NICU to be wireless and faster with improved sensors

One of the major sources of difficulties for the nurses comes from the vital sign monitoring of the babies. Typically all vital signs are monitored by attaching a sensor via a wire or cord to the patient monitor, which handles the signal processing and displays the vital signs. The participants named three main things they would like to see with vital sign monitoring in the NICU. First, one of the major things the participants stated was that they would like the sensors to be wireless:

Cordless. Absolutely cordless, yes, or something where you didn’t have so many wires everywhere. It’s like you’re trying to change a diaper and it’s like the ECG wires and the pulse ox and everything’s in the way. I’d love to have a cordless pulse ox. I don’t know if they could do that with ECG but whatever you could do would be great. (P4)

Second, several participants stated that they would like the sensors to collect data faster, especially external blood pressure: “[The babies] just don’t like getting their blood pressures taken, obviously, because it gets tight and I wish that the blood pressures would read faster. I feel like sometimes it just takes so long to get the blood pressure reading that I wish it would just do it and then read it.” (P6). Finally, several participants stated that they would like the sensors to better fit the tiny size of the babies in the NICU, especially the pulse oximeter:

I would have to say the pulse oximeters are probably more of the issue that they fall off... I don’t know if it could be like a like a sock kind of thing, a little bit more secure. We do tend to put like a sock over the baby’s [pulse ox sensor] just to hold it in place and so they’re less likely to fall off. If you have a nice tight fitting sock over that and less [external] light gets to the monitor too so it does have a better waveform. (P5)

Participants also stated that they need several size options to cover the vast range of sizes of NICU babies, especially as the babies grow bigger in the NICU over time:

The pulse ox, the bigger they get the less it will pick up. It’s designed for neonates. So, if you have an eight-month-old kid

Table 5. A summary of the nurses’ suggestions for future monitoring technologies.

The nurses wanted improvements to the vital sign monitoring infrastructure in the NICU	The nurses wanted the monitoring sensors (e.g., cuffs, leads, electrodes) to be wireless
The nurses wanted several ideas for reducing false and non-actionable alarms	The nurses wanted the monitoring sensors to fit better The nurses wanted the monitoring sensors to work faster (e.g., for blood pressure) The nurses wanted the monitoring system to reduce the occurrence of false alarms caused by the babies’ natural limb movements The nurses wanted the monitoring system to have the alarms automatically stop when the nurse is interacting with the baby
The nurses wanted the ability to customize both the visual and audible elements of the patient monitor	The nurses wanted to have the authority to tweak the alarm thresholds for vital signs The nurses wanted to continuously monitor vital signs of the babies’ assigned to them in real time
The nurses wanted improvements to the design of the NICU phone	The nurses wanted the ability to customize the alarm sounds on the patient monitor The nurses wanted the ability to view the vital signs on a smartphone-like phone so they could view all of their babies’ vitals at the same time The nurses wanted the phones to have physical buttons so they could easily accept and reject alerts without having to look The nurses wanted to receive a video feed of the babies to sanity-check the alarms The nurses wanted to use a voice interface to accept or reject alerts on the phone and alarms on the patient monitor

who is still in NICU for whatever reason and they're not having oxygen issues, then we can get rid of that and just keep them on the ECG but that doesn't happen very often. (P4)

7.2. The nurses suggested three areas of focus that would make the most impact for them with respect to reducing false and non-actionable alarms

It is well understood that the problem of false positive and non-actionable alarms is a big one in a NICU (Tanner, 2013). It is not surprising that the participants talked about alarm fatigue, given the preponderance of false and non-actionable alarms. The participants felt there were three main areas where improvements with respect to false and non-actionable alarms would make the most impact. First, babies are predisposed to kick and move their limbs. Not surprisingly, one of the biggest sources of false alarms is the babies' moving their limbs. The participants wanted these well known and understood sources of false alarms to be mitigated:

I mean, if you could solve the problem of the pulse ox always false alarming when they're kicking their foot around because that's a big issue There's different sizes. I don't know if we need more sizes or like if the stickers aren't sticky enough that hold it in place but those are not great. (P1)

Second, the participants wanted the monitoring system automatically to know not to send alerts on the phone (requiring the nurse to accept them) when the nurse is in the room taking care of the baby who is generating that alarm. After all, the patient monitor already generates an alarm in the room:

I would love for the phones if, when I walked in the room, it would stop giving me a text message alert that the monitor is alarming so that it... because a lot of the times it's just false alarming during care because you're moving the baby around but I'm in there and I know that it's me causing that. I mean, it's one thing for the monitor to go off but to also have to click accept on your phone for every single time, every two minutes while you're in there, it's just very cumbersome. Like if it knew I was in the room and it would stop texting me that this baby's having problems that I'm causing, that would be super helpful because you could be in and out of there a lot quicker because you wouldn't always have to be accepting the message on your phone - but you have to accept it or else it goes to your buddy and then they come over and then they see that you were just being lazy and didn't accept your own [alerts] and that gets annoying if you're always getting somebody who like leaves their phone at the desk or doesn't take it into the room because they're going to be in there. So that: if it could know where I was and stop all the extra alarms for things that I'm clearly right in front of, that would be good. (P1)

Not surprisingly, when asked whether the patient monitor alarms should be stopped as well as the phone alerts when the nurse is in that patient's room, some participants clarified that they would still want the alarms on the patient monitor in the room, especially when they are not facing the baby or the monitor (e.g., when preparing food or medicine or while charting): *"There are some circumstances where you wouldn't want to [silence the patient monitor alarms]. Like if I have my back to the [patient monitor], I wouldn't do that."* (P3).

Third, they noted that the nurses wanted the authority to slightly adjust the vital sign ranges as that would significantly reduce the number of non-actionable alarms. However it would require an update to the larger NICU workflow to make changing the thresholds easier. Moreover, there has been resistance from physicians even to modifications of these ranges that are done in accordance with current policy, that is, with physician approval: *"We've been looking for years at possibly expanding our parameters on our monitors but there's a lot of hesitancy from the physicians, which I get."* (P3). As we saw above, the nurses are well aware of when it is and is not safe to slightly adjust the thresholds.

7.3. The nurses wanted the ability to customize both the visual and audible elements of the patient monitor

Another major improvement that most participants mentioned was to be able to continuously monitor all their (four) babies on one screen, which is currently not possible: *"I wish that you could pull up all four of your babies all at once... I wish you could have them all up because sometimes they're all acting foolish and you want to see them all but that's not an option."* (P1).

Further, given the negative effect of the alarms on the babies and their parents, many participants wanted at least to reduce the volume of the alarm sounds on the patient monitor, if not remove these sounds from the patient rooms:

It'd be kind of cool to have all the alarms just on my desk, a little device on my desk that I could just program and get it completely out of the patient room. That way it's not keeping the baby up or they don't, the baby's not listening to the alarms going off or the families don't have to listen to it. (P2)

Another suggestion from the nurses was to re-design the alarm sounds on the patient monitor to: (1) be easier on the ears, especially because there are so many false and non-actionable alarms: *"I wouldn't be 100% opposed to [changing the alarm sounds] as long as it was a little bit more gentle to the ears."* (P2) and (2) give nurses the option to customize the alarm and alert sounds, so as to make the sounds for a sensor that has fallen off distinguishable from the sounds for a negative change in a vital sign: *"... or let the [alert] sound be different or something so that when it comes to my phone, I know that it's just not picking up well and not that the heart rate's dropping."* (P4).

7.4. The nurses suggested several ways to improve the design of the NICU phone

Not surprisingly, the functionality of the phone was a source of considerable frustration for the participants. Consequently, they suggested several ways in which the phone's design could be improved.

- **Smartphone-like phones with the ability to view in real time the vital signs of all the babies assigned to them:** The participants wanted the phone to be more

smartphone-like so it could replicate and augment the patient monitor by allowing the nurses to view the same continuous vital sign information that the patient monitor shows, only for all of their babies at the same time:

... it's just a text like you would get on an old flip phone kind of thing. Whereas if we had some sort of a smartphone... if I can't pull multiple [patients] up on [the patient monitor], I have my smartphone and maybe I can put another monitor on my smartphone and have that in a spot where I can see it. So you can see it in real time, you'd say, 'okay, the sat was 80 but now it's 95.' (P3)

Even though newer versions of this phone are smartphone-like, it seems this hospital thus far has not upgraded their phones:

We looked at other phones a few years ago and I don't know what happened. It fell through. They're supposed to be more like iPhone, like where you could maybe view the monitor. I don't know what exactly it could do. It was supposed to have more functions and then we ended up not doing that. (P3)

- **Physical buttons on the phone:** The participants wanted to maintain physical buttons on their phones and not have a purely touchscreen interface. Currently, the raised physical buttons on the phone allow the nurses to accept alerts without looking at the device (when they are doing other things to take care of the babies): "... *sometimes when I'm doing care and the [alert] goes off, I can feel which [button] is accept and which one's reject. So if it was touch screen, I'd have to actually look at it. So definitely not that...*" (P7).
- **Video feeds from the patient rooms:** Some participants stated that they would like to use their phone to selectively view a video feed of the babies, especially in the event of an alarm. This would allow them to get more context about the baby while sanity-checking the alarm: "... you get the [alerts] but it would be really cool to have on your phone a Facetime situation where you could see your baby and could see them, like: are they tucked in? are they wiggling around? So you'd know, 'oh, they're just kicking, that's why it's going off.' So you'd get the [alert] and then you get an actual live monitoring of what the baby is doing in the room. That would be something. (P6)

However, one participant warned against the over-reliance on the use of video feeds to know the status of the baby:

I think that if I was looking at a baby on a camera, I wouldn't really be able to appreciate a little bit of dusiness in the baby's face.... Some babies will spit up and then they'll have a drop in their heart rate and oxygenation. You're like, 'oh, he or she doesn't usually do that. I wonder what's going on.' You walk in there, they've got spit up all over them. I don't know if you can appreciate it if it's not completely right in the view of the camera. (P2)

- **A voice user interface on the phone and patient monitor:** Several participants also suggested the use of a voice user interface to interact with their phone and the patient monitor, especially as a way to accept or reject alerts and alarms:

You know, actually what would be helpful is if we had like a voice command. You know, to say 'accept [alert],' 'decline [alert]' rather than having to get the phone out, hit the accept

button or the decline button or silence alarm. Even the monitors, if we have like a voice command where we could say, 'silence alarm.' I don't know how safe that would be but, yeah, maybe like a voice command kind of thing. (P5)

8. Monitoring technologies should be designed to empower NICU nurses

In this paper, we focused on developing a broad understanding of the challenges nurses encounter when using the monitoring technologies in a NICU. To wit, we interviewed seven nurses who work at a NICU in the US. We found that NICUs have monitoring technologies in place to help the nurses do their job effectively, given factors such as the individual room layout of the NICU as well as increased baby assignments. However, the design of these monitoring technologies, which was never specific to the NICU, also creates impediments for the nurses that add to the nurses' workload. *Consequently, we contend that: (1) monitoring technologies in the NICU should be designed specifically to be used in the NICU and (2) this design should center the nurses and their needs.* Therefore, in this paper we argue that one of the ways to reach these two goals is to rethink the design of monitoring technologies as a way to *empower their primary users, the NICU nurses*. We use the term empower to mean: (1) giving NICU nurses more control over the monitoring of the babies and their environments – we designate these below as MBs; (2) giving NICU nurses the ability to control the operation of the monitoring technologies themselves – designated as MTs. Below we discuss six broad areas of future research aimed at designing monitoring technologies that empower the NICU nurses. For each research area, we list a few specific research questions that we believe should be tackled.

8.1. MB 1: Designing a vital sign monitoring infrastructure that facilitates kangaroo care

Kangaroo care or skin-to-skin contact between a parent and their baby has considerable benefits for the baby, including promoting physiological stability (Mitchell et al., 2013), stress relief (McCain et al., 2005; Mitchell et al., 2013), pain relief (Cong et al., 2012; Johnston et al., 2017), weight gain (Conde-Agudelo et al., 2012), improved sleep (Hauser et al., 2020), brain development (Korrraa et al., 2014) and even helping reduce hospital stays and medication for substance-exposed babies (C. K. Johnson, 2023). Given this, kangaroo care is encouraged in a NICU for all infants (even extremely preterm ones) as soon they are stable (Karlsson et al., 2012). However, as discussed in the findings section, the current monitoring infrastructure is suboptimal for the nurses to facilitate kangaroo care. Based on our findings, one of the main reasons for these issues is that the sensing infrastructure in a NICU was never designed specifically for the needs of the NICU environment and newborn or premature babies. We believe that new approaches are necessary that will enable the design of new monitoring systems in the NICU that work to facilitate kangaroo care. In this regard the infrastructure should be designed with the following properties: (1) be

wireless in nature; (2) use leads/electrodes with a form factor that facilitates maximum skin-to-skin contact between the baby and parent; (3) reduce noise in the measurements from motion artifacts produced from moving the baby between the bed and the parent as well as the baby's natural inclination to move its limbs; and (4) have leads and cuffs that fit and adhere appropriately so that they neither introduce noise from all the movement inherent to kangaroo care nor attach to other surfaces such as the parent, thus producing false alarms and alerts. Further, as it is the NICU nurses who facilitate kangaroo care, we argue that designing to satisfy these properties should necessarily involve the NICU nurses, in order to understand the nuances of kangaroo care. Recent work in designing pulse oximeters for the NICU is a great start in this regard (Chung et al., 2019). However we have to expand this work to other types of sensors as well.

Some of the research questions that we have to consider in this regard include:

- What are the nuances of kangaroo care as practiced by nurses from a variety of NICUs?
- How can we use input from the nurses about kangaroo care to design kangaroo-care-friendly sensing hardware and signal processing tools for monitoring the vital signs of importance in the NICU?

8.2. MB 2: Introducing nurse-controlled video feeds in patient rooms for improved patient monitoring and alarm management

One of things the nurses wanted is a system that would automatically know when they are present in the room with the baby and thus silence: (1) all alerts on the phone and (2) alarms on the patient monitor, only when they are facing the monitor or interacting with the baby. One of the ways to do this would be to introduce a nurse-controlled video camera in the room. Several studies in the literature looked at perceptions of using cameras in a NICU, though only from the standpoint of parent/child bonding (Hawkes et al., 2015; Joshi et al., 2016; Kilcullen et al., 2020; Rhoads et al., 2015, 2012). To the best of our knowledge, no work has been done that uses video streaming that improves the nurses' ability to do their duties in the NICU and is in their control.

The video captured by the video camera could be used to constantly monitor who is present in the room and then silence phone alerts for that baby for the entire time the nurse is present in the room. Further, the system could then selectively silence the alarms on the patient monitor when the nurse is in the room, taking care of the baby and then turn the alarms back on when the nurse is not facing the baby (while in the room). The presence of such a video camera in the room can have other alarm-management benefits as well. Nurses in a NICU take care of several babies. Therefore when an alert sounds, the nurses are often busy taking care of the needs of another baby. We believe that video feeds in the rooms would allow the nurse to see the alarming baby's appearance and affect, in addition to the baby's vital signs (which the nurse can already pull up on

the other baby's patient monitor), to make an even better informed decision on when to act than they could with just access to the vital signs alone.

However, introducing video feeds into the patient room is not without its risks. Care needs to be taken to ensure that the video feeds only would be used for clinical purposes and preserve the privacy of the baby, the parents, visiting families and the nurses. It is imperative that the video feed not be used as a surveillance mechanism on the nurses, the parents, or anyone else. Thus any video feed should only be: (1) used with the consent of the parent/families and nurses and (2) only visible to the nurses. Further, processes should be put in place to ensure that the availability of video feeds would not build complacency that would prevent the nurses from checking on the baby in-person. As a participant mentioned, no matter the fidelity of the camera used, it cannot provide all of the information available in-person and what it can provide is not necessarily as reliable or accurate as what can be observed in person.

Some research questions in this area include:

- What are the best policies to put in place for introducing consent-driven, privacy-preserving video feeds in patient rooms in a NICU setting?
- How to design real-time video-processing models that can specifically identify the presence of the baby's nurse in the room to disable the alerts altogether and, for the alarms, disable any alarms that occur while the nurse is facing the baby?
- How to redesign and leverage the nurses' phone such that it can act as a point for private viewing and centralized control of the video feeds?

8.3. MB 3: Designing a new smart device interface to enable nurses to centrally monitor and document the baby's state

One of the biggest problems for NICU nurses is that they are not able to see the state of all of the babies in their care in real time. This has especially become a problem as the number of babies assigned to each nurse has increased, as a result of the NICU nurse shortage. Further, the nurses regularly and often have to document the state of the babies during their stay in the NICU, which is done through a separate computing terminal in the patient room (see Figure 1(f)). This constant documentation increases the nurses' workload and often also their stress level. The current monitoring and documentation systems in place are fundamentally unsuited for a NICU, where more than two babies per nurse is the norm and the nurse is constantly on the move between the babies assigned to them.

In short, given how busy NICU nurses are, it would be better to have a common portal that provides flexible monitoring for all the babies in their care. Ideally, such a system would also improve the charting process, e.g., by allowing copy-pasting. One way might be to introduce a small tablet-like device, which would allow the nurse to monitor and document the baby's condition from the same device by

supporting: care-time charting, viewing and controlling the video feed mentioned above, viewing the continuous and instantaneous vital signs of all the babies in their care, receiving alerts, and accepting and rejecting alerts on it. Further, the device could have appropriate, easy-to-use authentication in place to allow only authorized nurses to control the device. However, unlike the current trend for tablets and smartphones, the device should not have an all-glass display and instead come with physical buttons as well. Physical buttons are essential to allow nurses the ability to receive, accept, or reject alerts by feel without having to look at the device. Even if such a device were to enable voice-based interaction for dealing with alerts, physical buttons are still needed as an option and a fail-safe in case of the phone's inability to understand the nurse's command in the din of the NICU. In other words, voice capability and physical buttons would both be needed to allow nurses a variety of ways to interact with the phone to accept alerts, depending on their preferences and the circumstances of the baby they are treating.

Some of the research questions regarding the design of a smart device for NICU nurses include:

- What kind of form factor would be appropriate for the smart device to allow the nurses to holistically monitor and document the state of all their babies simultaneously?
- How to integrate this device into the NICU workflow? For instance, would it be something the nurses carry, like their current phone, or would it be a bedside tablet, or a tablet in the hallway at the nurses' station?
- How to design fast and secure authentication mechanisms such that only authorized nurses would be able to use the smart device (especially for a bedside device where the parents/families would be present)?

8.4. MB 4: Exploring augmented reality (AR) glasses for NICU nurses

In the medium term, efforts should be made to consider the feasibility of wearable computing technologies, such as augmented reality (AR) glasses, to ease the burden imposed by the high workload and the nurses' need to manage the monitoring technologies. Such a setup would allow the nurses to be able to view the video feed and vital signs of any of their babies anytime they want while leaving their hands free. Further, the AR glasses could be configured to both receive and accept/reject alerts via a voice interface. One could also imagine including an outward-facing camera on the AR glasses to determine the nurse's location in the NICU and when they are facing the baby and/or patient monitor, thus allowing for the alarms and alerts to be disabled appropriately.

Some of the research questions regarding the use of AR glasses for NICU nurses include:

- How would the AR glasses impede the nurse's ability to perform their duties, if at all?
- How would the nurses feel about having to wear AR glasses while working in the NICU?

- How would we integrate these AR glasses into the NICU workflow?

8.5. MT 1: Using voice commands to handle the alerts and alarms

One of the biggest issues the nurses have with the NICU phone is that they have to accept the alerts on the phone for often false or non-actionable alarms, especially when they are busy with the needs of a baby. The demands of the phone often require them to go to extraordinary lengths to press the accept button on the phone, such as pressing it with their chin or elbow. One of the ways to address this problem might be to implement voice commands on the phone as an additional option that would allow the nurses to accept or reject alerts hands-free so they can continue doing their current task. However the NICU is a busy place with a lot of different types of people (physicians, nurses, parents, families, therapists, etc.) intermingling along with a lot of ambient sounds produced by all the equipment in the area (Freudenthal et al., 2013). Therefore, phones accepting voice commands would have to be specifically designed and tuned to work in this environment, including the layout of the specific NICU where they are deployed. For instance, it should not be possible for a nurse in an adjoining room to silence the alert on another nurse's phone by mistake because of their loud voice.

A few participants also stated that they would like to have voice commands to manage alarms on the patient monitor as well. However care needs to be taken so it is done in a *safe* manner. Unlike the phone, which is only accessible to the nurses, the patient monitors are accessible to anyone in the patient room. Therefore, handling alarms on the patient monitor using voice commands in a safe manner would require that the patient monitor only accept commands from the nurse assigned to the baby in that room.

Some research questions in relation to introducing voice commands for handling phone alerts and patient monitor alarms include:

- How to design voice commands such that nurses can easily accept or reject phone alerts in the NICU?
- How to leverage the hands-free nature of the voice interface to try new strategies to manage phone alerts produced from false and non-actionable alarms, such as accepting alerts in batches rather than one alert at a time?
- How to use voice commands to handle alarms on the patient monitor?
- How to ensure that the phone and/or patient monitor accepts the voice commands of the nurse assigned to that device/patient and not anyone else's?

8.6. MT 2: Expanding options for alarm sounds in the patient room

When some instantaneous vital signs of a baby go above or below a preset threshold, an audible alarm is produced at

the patient monitor in the room. As discussed in the findings section, the alarm sounds can be disturbing and stressful not only to the babies but also to their parents and the nurses as well. The stress that the noise introduces to the babies has been documented in prior work (Freudenthal et al., 2013; Laubach et al., 2014). However, to the best of our knowledge, not much work seems to have been done to propose any solutions. Some efforts, such as muting the sound of clinically less relevant RespR alarms and associating a different tone with them, are a step in this direction. However it appears that the alarms sounds generated by the patient monitor are designed to be harsh and thus easy for nurses to hear even if they are not in the vicinity of the alarming baby. However we believe that the alarm sounds could be redesigned specifically for the NICU context by considering the following: (1) the abundance of false and non-actionable alarms in the NICU, (2) the effects of the alarm sounds on the baby's well-being, (3) the layout of the NICU, and (4) the use of phones in the NICU, which could change the calculus for how far the alarm needs to be heard. Finally, the ability to change the alarm threshold currently rests solely with the physicians, who are often reluctant to update the thresholds. Perhaps more authority could be delegated to the nurses to tweak the alarm thresholds, as way to handle and reduce the disruption from non-actionable alarms. A very interesting approach to dealing with alarms is described in the paper (Cabrál Guerra et al., 2019), which uses the notion of peripheral interaction to develop beepless connectors, visual indicators to reduce unwanted alarms, especially when the nurse is interacting with the devices on the baby in a NICU. However it is not clear how well this approach would work under the high workload conditions of NICU nurses like our participants.

Some of the research questions in this regard include:

- How to give nurses options so they can customize the alarm sounds specifically for their needs?
- Would NICU nurses like to have the option of visual indicators in high workload situations?
- How to update the NICU workflow such that nurses have the authority to tweak the alarm thresholds for babies in their care, as needed?

9. Limitations

The methodology of our study had four main limitations that we briefly discuss. First, all participants we interviewed worked in the same hospital's NICU. We do not believe that this affected the observations in the paper; however, a more diverse set of nurses from other NICUs around the country could have provided additional perspectives that we might have missed here. Second, all of our participants were from the US and, therefore, their perspectives and experience may differ from those of nurses from other regions of the world. Third, the hospital where the NICU is situated is one of the safety net hospitals in its region, which means it has to provide care for people regardless of their insurance status

(Safety Net Hospitals, 2023). In the US, such hospitals typically have fewer resources because of the types of reimbursement they largely receive. Consequently, the opinions of the participants may perhaps generalize to a lesser extent to better resourced hospitals. Finally, the NICU where our participants work uses a phone-based system to allow the nurses to keep track of the babies in their care. However, not all NICUs in the US may use such a system. No clear statistics are available on how many NICUs in the US rely on similar phone systems. Some press reports have suggested that about 28% of US NICUs use phones (NICU Phone, 2017). Therefore our analysis about phones and alerts in this paper may not generalize to NICUs that do not use phones. Further, newer models of NICU phones have smartphone-like, buttonless, glass interfaces (NICU Phone, 2017). The NICU where our participants work uses a phone that is more like a feature phone rather than a smartphone. Consequently, the generalizability of our analysis pertaining to handling alerts on the phone may also be limited.

10. Conclusions

The neonatal intensive care unit (NICU) provides an environment that is optimal for the health, recovery, and growth of infants who are born preterm or who have various health issues at birth. Bedside nurses form the backbone of the staff that cares for the babies during their stay. Since each bedside nurse in the NICU is responsible for multiple babies at a time, they use a variety of *monitoring technologies* to track the health of the babies in their care. These technologies help the nurses in the monitoring of the babies under their care in a way that is essential for the successful operation of the NICU. However many elements of the monitoring technologies in a NICU are repurposed from devices used in the rest of the hospital (i.e., mostly for adult patients). To understand how these monitoring technologies function in the NICU *from the viewpoint of the nurses*, we conducted one-on-one semi-structured interviews with seven nurses who work at the NICU. Overall we found that all elements of the monitoring technologies impeded the nurses' ability to perform their duties in some way. Further we found that, in some limited situations, nurses were able to rely on their experience to find interesting ways to cope with the challenges that the monitoring technologies posed. Given the difficulties the monitoring technologies posed to the nurses, the latter also suggested several improvements to the monitoring technologies. We ended the paper by arguing for the need to rethink the design of monitoring technologies in a way that empowers and centers NICU nurses. We thus discussed six broad areas of future research aimed at designing monitoring technologies that empower NICU nurses.

Notes

1. These are monitors from a company called Space Labs (Spacelabs Healthcare, 2023). The current line of monitors was installed in 2019–2020.
2. We use *sensor* as a catchall term to mean lead, cuff, probe, or electrode – the element of the monitoring system that

actually attaches to the babies' body and measures physiological phenomena of some form.

3. The phones were manufactured by a company called ASCOM (ASCOM Phones, 2023). These phones started to be used when the NICU was updated to individual rooms. Since then there have been some updates, so the current set being used is a combination of 12-year-old ASCOM phones and newer models.
4. Babies can be positioned on their belly, on their back with their head elevated, or on one side with the help of specially designed pillows. Many nurses mention that it is important to reposition the babies often to make sure their head does not become misshapen from being in the same position for too long. The nurses also reposition the babies to help them with digestion, where their head is propped up, or to help them with breathing, by putting them on their belly.

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