Case Study

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Lean Design of the Pediatric Intensive Care Unit Patient Room for Efficient and Safe Care Delivery

Yuqian Lu, MA[1], Naomi B. Bishop, MD[2] and Rana Zadeh, PhD, MArch[3,4]

Abstract

Background: The pediatric intensive care unit (PICU) is an environment where seriously ill children receive complex care, delivered mostly by specialty-trained nurses (registered nurses [RNs]) who must perform multiple high-level tasks. With stressors on healthcare systems at an all-time high, design that optimizes RN workflow has taken on a renewed imperative. **Objectives:** To employ a multi-modal approach (1) to identify environmental factors in the PICU patient room that contribute to caregiver workflow inefficiencies, (2) to optimize safety by identifying high-touch surfaces that cause hospital-acquired infections, (3) to develop human-centered design recommendations. **Methods:** This mixed-method case study was conducted in a 23-bed urban hospital PICU. The activities, movements, and workflows of 13 RNs were recorded using spatial movement mapping, behavioral mapping, and clinical activity mapping. Frequency of RN contact with surfaces was documented to assess relative infection transmission risk. Face-to-face interviews were conducted with RNs to elicit their views on care delivery and their physical work environment. **Results:** Direct patient care occupied 50% of RNs' time. Of the direct patient care workflow activities recorded, 26% were to prepare for care around the bedside, while 27% were for random travel between clean and soiled areas. The surfaces most frequently touched were (1) patient bedrails, (2) intravenous pumps and poles, (3) tubing and medical equipment, and (4) vital sign monitors. **Conclusion:** Value-added tasks account for only about 20% of nurses' work. Combining technology and strategic interior design to streamline workflow and enhance infection prevention optimizes efficiency and empowers frontline providers to maximize their time at the bedside performing value-added tasks.

[1] Department of Human Centered Design, Cornell University, Ithaca, NY, USA
[2] Department of Pediatric Critical Care Medicine, Weill Cornell Medicine, NY, USA
[3] Department of Human Centered Design, Cornell University, Ithca, NY, USA
[4] Faculty of Medicine, University of British Columbia, Vancouver, BC, Canada

Corresponding Author:
Yuqian Lu, MA, Department of Human Centered Design, Cornell University, Ithaca, NY, USA.
Email: yl2752@cornell.edu

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Children admitted to pediatric intensive care units (PICUs) often suffer complex and chronic diseases with high morbidity and mortality (Namachivayam et al., 2010). The physical environment of the PICU patient room is a critical space where most of the medical care is delivered (Joseph et al., 2018). Front-line registered nurses (RNs) in the PICU are highly skilled specialists who must execute a complex patient care plan while monitoring the patient continuously and interpreting multiple streams of data (Bratt et al., 2000). The work environment is highly demanding due to frequent exposure to traumatic events, unexpected changes in acuity, and the suffering of children and families (Rodriguez-Rey et al., 2019). Optimizing nurse workflow in the PICU patient room is particularly important for the delivery of safe and efficient care (Hendrich, 2008).

Hospital work environments are burdened with inefficiencies that stem from the design and organization of the physical space; specifically, the inappropriate room and equipment arrangement, crowded and insufficient workspace, misplaced equipment, and unorganized supplies (Gurses & Carayon, 2007). The consequences are felt strongly, especially by those providing care to the vulnerable pediatric population (Pati et al., 2012; Zimring et al., 2013). An inefficient system increases nurse stress levels, reduces work efficiency and effectiveness, and may lead to increases in medical errors (Roseman & Booker, 1995; Ulrich et al., 2008). These inefficiencies may also translate into serious health consequences for patients, such as increased hospital-acquired infection (HAI) rates and longer lengths of stay (Zimring et al., 2004). Patients are not the only ones to be negatively affected; their caregivers experience additional emotional distress and burnout following serious medical errors (Waterman et al., 2007). When added to the stress imposed by the loss of autonomy over decision-making about their child's care, complex logistics of caring long-distance for healthy siblings, sleep disruptions by jarring light and sound, and self-care neglect, the toll can be significant (Jee et al., 2012; Smith et al., 2007). Healthcare institutions are also impacted by such events; U.S. hospitals pay more than $30 billion every year to compensate for preventable medical errors and HAIs (Khon et al., 2000).

Functional work efficiency can be defined as the movement required to complete an activity (Pelletier & Thompson, 1960). A set of activities, the resources needed to accomplish the activities (such as RNs, equipment, or spatial arrangement), and how these interact comprise a workflow (Thompson et al., 2003). An efficient workflow produces a desired result while reducing redundancy and interruptions (Zadeh et al., 2012). The unoptimized and inefficient physical environment in hospitals leads to excessive and unnecessary walking by staff (Pati et al., 2012; Zimring et al., 2013). This activity is non-value-added work or waste in Lean design (Thompson et al., 2003). Eight major sources of waste in nurses' daily activities have been identified as "disjointed supply sources, missing or non-functioning supplies and equipment, repetitive travel, interruptions, waiting for systems/processes, difficulty in accessing resources needed for care, breakdown in communication, and breakdowns in communication processes or mediums" (Ebright et al., 2003). Most wasted activities can be removed by reducing interruptions and aligning caregivers' work patterns with their movement sequences (Potter et al., 2005; Zadeh et al., 2012).

In the course of their duties, RNs provide "direct patient care, critical communications, charting, filing medications, access to technology and information, and other tasks [activities]" (Ulrich et al., 2008; 49). Their interaction with the physical environment of the patient room is complex (Holden et al., 2013). Supplies and surfaces around the patient bed may become sources of microbial pathogen transmission which may ultimately lead to HAIs (Cobrado et al., 2017). RNs' hands may be vectors for direct and indirect transmission of pathogens (Ulrich et al., 2008) through repeated contact with high-touch surfaces. The frequency of contact with these surfaces can be reduced by understanding their interactions with the work system, that is, the physical environment, the medical equipment, and care delivery activities, and optimizing RN workflow within it (Anderson et al., 2010; Cohen et al., 2014). The healthcare environment should be designed to support care delivery, especially for vulnerable, high-risk, critically ill children.

This study is intended to add to the paucity of publications on PICU workspace design. We show that by applying Lean principles and evidence-based design methods, RN work efficiency and patient safety can be enhanced. Adopting an interactive, nurse-centered healthcare design approach allows for insights that may lead to more effective and durable solutions. Our study had three aims: (1) to improve workflow efficiency by reducing wasted activities and extra walking during the care delivery process, (2) to promote safety by identifying equipment surfaces that increase the risk of infection transmission, and by establishing activity patterns that direct flow from clean to dirty zones, and (3) to offer human-centered spatial design recommendations for the PICU clinical care area with added focus on the work zone around the patient bedside.

Adopting an interactive, nurse-centered healthcare design approach allows for insights that may lead to more effective and durable solutions.

This study provided the basis for design recommendations to better support RN work efficiency and ensure care quality in PICU multi-bedded patient rooms. We recognize that for more than a decade, the trend in ICU design has been away from the open-bay (OB) and multi-bedded rooms and toward single-family rooms (SFR); however, in a 2022 study of 161 U.S. PICUs conducted by Ista et al., 30% still had multi-bedded rooms (Ista et al., 2022). These semi-private and OB arrangements would benefit from our findings and suggestions. In addition, many of our findings highlight design concerns around the bedside that apply to SFR arrangements as well.

It is notable that while there is general consensus that families benefit from the increased privacy, noise reduction, and stress reduction afforded by private rooms (Verderber et al., 2021), the transition from the OB and SFR design has not been universally well received by ICU nurses. When surveyed, some reported increased isolation from other staff, less opportunity for teamwork, farther distances to supply and utility rooms, and less opportunity for direct, in-room monitoring of their patients (Smith, 2016).

Methods

Research Design

This qualitative and quantitative mixed-methods case study was designed to identify sources of RNs' wasted activities and to propose changes to the physical environment, amenities, and workspaces in the PICU patient room that support speedy and safe nursing care. Toward this end, we captured the RNs' workflow and recorded their interactions with several environmental factors within the patient room.

We employed direct observation to graphically track RNs' spatial movements, clinical activities, and equipment surface contact frequencies. In-person, semi-structured interviews were conducted with RNs to elicit their perceptions of the work environment and workflow. The study was approved by the hospital and university institutional review boards.

Site Selection

The study was conducted in the PICU at a large metropolitan hospital that serves as the biomedical research hub and medical school of the university attended by the primary investigator. The unit houses 23 patient beds, spread over 3 single, 1 double, and 6 triple-bedded patient rooms. There are 1,200 medical-surgical admissions per year. We selected a triple-bedded patient room with an in-room nurse workstation for our observations and data collection since this arrangement comprises the majority of rooms in this unit. The

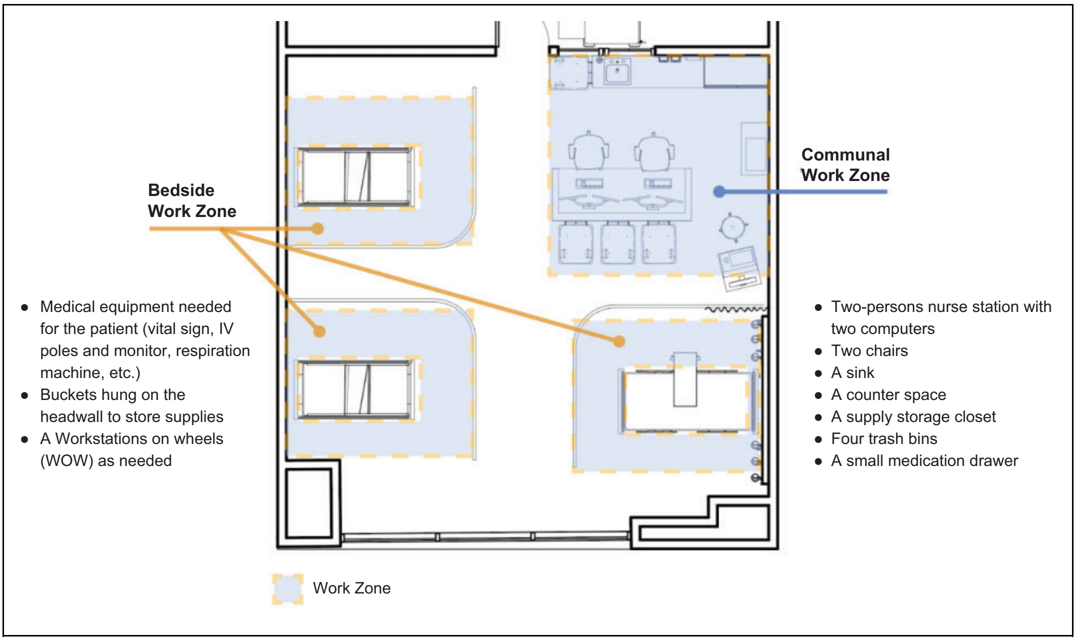

Figure 1. Triple-bedded patient room work zone diagram.

triple-bedded rooms are approximately 650 sq ft., each patient bedspace is about 145 sq ft., and the nurses' communal work area is about 130 sq ft., in keeping with the most recent Facility Guidelines Institute guideline of allocating approximately 150 sq ft. per patient to *clear floor area* (Facility Guidelines Institute, 2018). Our observations and recommendations pertained to RN work efficiency and safety, and focused on the RN bedside and communal work zones (Figure 1).

Participants

For the observation portion, this study enrolled RNs working in the PICU who agreed to participate ($n = 13$). This number represents 41% of the total pool of dedicated daytime nurses ($n = 32$). On a typical day in this PICU, the staffing goal was 14 primary RNs. The nurse to patient ratio was 1:1 or 1:2 based on the patient's acuity level and the number of available staff. Six of the 13 RNs agreed to both the behavioral observation and interview. The participating RNs ranged in age from 20 to 35 years. RNs who worked in the PICU for less than 1 month at the time of this study were excluded. The study was announced through email and during a monthly staff meeting held by clinical nurse leadership. Nurses who were interested in participating were briefed about the research process and study goals, and provided verbal consent. All families in the study provided verbal consent for observation after discussion with their primary RN. No identifying or personal information related to the patients or families was recorded or documented.

Data Collection and Analysis

Quantitative data collection employed human–environment interaction and Lean methodology. The primary tool was an observation sheet with three elements: a spatial movement map (Figure 2), a clinical activity map (Figure 3), and a surface contact transmission map (Figure 4). Qualitative data collection included behavioral observation and interviews.

The quantitative tools, interview, and observation processes were informed by literature review and developed in consultation with experts. Proof of concept was tested on prototypes during a 6-hour pilot study in a triple-bedded patient room

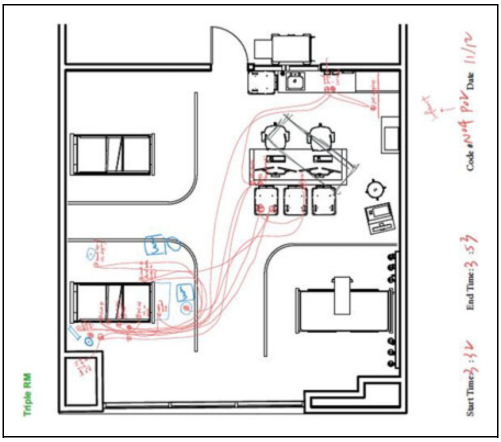

Figure 2. Observation worksheet: Spatial Movement Mapping.

at the same institution conducted 1 month before formal data collection.

Quantitative Measures

Spatial Movement Mapping (SMM): SMM followed the Lean approach and aimed to record the RNs' movements and activities during care delivery. A detailed floor plan showing the location of RN work areas, patient bed spaces, surrounding equipment, and furniture was incorporated into the observation worksheet during the pilot study and functioned as the map base (Figure 2). The map enabled objective documentation of the type and sequence of the RN activities. During the observation, sequence numbers were assigned to each activity conducted by the RN. If the RN moved from one location to another during care delivery, a line was drawn on the floor plan to show the walking path.

SMM was graphically analyzed and the top six functional locations for nursing activities were identified. By counting the number of RN spatial movements between these areas, the researcher reconstructed the traffic flow. An adjacency diagram was used to analyze the hierarchy of traffic flow in relation to spatial proximity. Each bubble in the diagram represents one physical space in the patient room. Three different line thicknesses were used to indicate three levels of adjacency; the thicker the line, the more walking that was observed. A higher traffic flow suggested a need for stronger physical proximity between the areas.

Clinical Activity Mapping (CAM): CAM included a list of relevant nursing activities developed from literature review and expert consulting consulting, and refined by the pilot study (Table 1). The three main categories of the map, *unit-related functions*, *nursing practice*, and *resource retrieval location* (Table 1; Figure 3), were developed from Hendrich (2008). *Unit-related functions* included preparing equipment and transporting a patient between departments or rooms (Hendrich, 2008). *Nursing practice* included six subcategories: medication administration, documentation, assessment/reading vital signs, infection prevention procedure, direct clinical patient care, indirect patient care, communication, and sampling blood for lab studies. These were also developed based on the Hendrich study (2008) and were refined by the clinical leadership who reviewed the categories. Further refinement based on the pilot study yielded the addition of a *resource retrieval locations* category to record the locations of resources and supplies.

While analyzing CAM data, the frequency and sequence numbers of one or more of the identified activities were recorded and coded into a single Excel spreadsheet.

Surface Contact Frequency Mapping (SCFM): To spatially mark the high-contact surfaces, a map of two axonometric drawings of the triple-bedded patient room was developed and placed on the back of the observation sheet. The drawings demonstrated the locations of the communal work zone and the bedside work zone in relation to furniture and medical equipment in the patient room (Figure 4). The equipment arrangement and room layout on the drawing were refined after the pilot testing. During each observation, the surfaces contacted by the RN and frequencies of these contacts were marked on the drawings.

The frequency of RNs' contact with all objects and surfaces captured in SCFM was computed and ranked on the Excel sheet. Detailed descriptions of activities and contact with surfaces were entered on the same Excel spreadsheet used for

Clinical Care performed				
Unit-related Functions		Unit-related functions	Prepare equipment	
Unit-related Functions		Unit-related functions	Transport patient	
Nursing Practice	Infection prevention procedure		Hand Hygiene	
Nursing Practice	Infection prevention procedure		Get hand soap / paper towel	
Nursing Practice	Infection prevention procedure		Wear PPE	
Nursing Practice	Serial monitoring of vital signs		Serial monitoring of vital signs	
Nursing Practice	Direct clinical patient care		Pick up supplies/medication	
Nursing Practice	Direct clinical patient care		observing the patient to evaluate their genera	
Nursing Practice	Direct clinical patient care	Check Iv status	Check the IV electronic readout	
Nursing Practice	Direct clinical patient care	Check Iv status	Untangling IV lines	
Nursing Practice	Direct clinical patient care		Suction patient	
Nursing Practice	Direct clinical patient care		Clean patient	
Nursing Practice	Medication administration		Prepare medication	
Nursing Practice	Medication administration		Medication administration	
Nursing Practice	Indirect patient care		Comfort/play with patient	
Nursing Practice	Indirect patient care	Clean pt. zone	Retrieval soiled supplies	
Nursing Practice	Indirect patient care	Clean pt. zone	Dispose soiled supplies	
Nursing Practice	Communication		Communicate with other care providers	
Nursing Practice	Communication		Communicate with family members	
Nursing Practice	Documentation		Documentation	
Nursing Practice	Sampling blood for lab studies		Lab works	
Nursing Practice	Others		Others (Explain)	
Resource Retrieval Locations			Around the bedside	
Resource Retrieval Locations			In Room (supply closet, nurse workstation)	
Resource Retrieval Locations			Outside of the room (medication room, tube	

Figure 3. Observation worksheet: Clinical Activity Mapping.

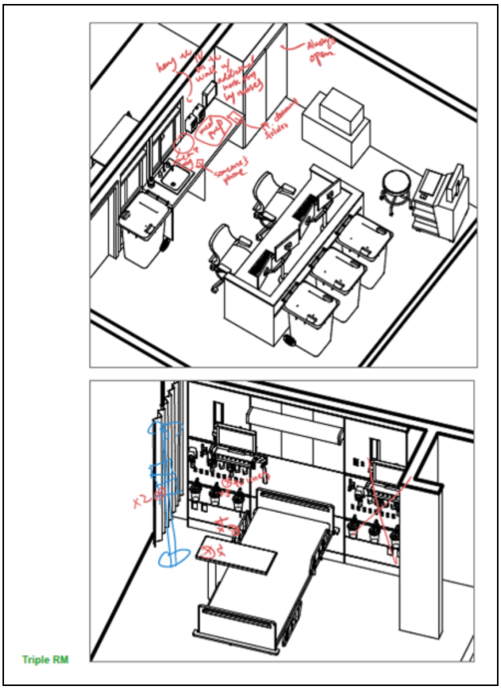

Figure 4. Observation worksheet: Surface Contact Frequency Mapping.

the CAM in order to associate the contact frequencies with the RN's activities.

Qualitative Measures

Behavioral Observation: Behavioral observation was conducted with 13 RNs. At the beginning of each observation, anonymous identifiers for the RN and her patient and the start time were recorded on the data collection sheet. The RN's spatial movements, care delivery activities, and high-touch surface contacts were documented during each observation. A total of 35 hours of observation were conducted in three identical spatial layout triple-patient rooms over five consecutive weekdays in November 2018. The usual RN day shift was 12 hours and started at 7:30 a.m. Daily observations began at 10:00 a.m., after the morning patient care rounds, and ended at 7:00 p.m., before the RNs' 7:30 p.m. shift change. The observer was stationed in the corner of the patient room, outside the sterile zone, with direct visual access to the entire room. The RN's movements, clinical activities and interactions with the physical environment were recorded via the tools developed during the pilot study. The start time and end time were recorded for each observation. Each observation session was defined by the RN's movements devoted to patient care activities, starting when the RN entered the patient room or left the workstation. All *unit-related functions* and *nursing practice* activities were included in the observation. RN activities at the workstation related to preparing, receiving, and recording of medications were included. The RN's time spent at the workstation completing patient-specific electronic charting was excluded to maintain patient privacy. Nursing activities apart from their primary nursing assignment were also excluded from the observation. Such activities included helping technicians and non-ICU staff to complete procedures (e.g., imaging studies) on their patients, assisting other RNs with preparing their patients for bedside imaging or intrahospital transport, preparing a patient bed space for a new patient, and non-work-related activities (e.g., personal phone calls, chatting with coworkers between activities, and organizing personal belongings). The session ended when the RN completed the care and returned to the nurse workstation or left the room. During the observation, the RN could notify the researcher at any time to pause the observation for the benefit and comfort of the patient or herself. This occurred, for example, when the RN determined a need to protect the safety, comfort, and privacy of her patient or the family (e.g., when bathing the patient).

Interviews: Semi-structured, in-person interviews with RNs were conducted to receive feedback about their work environment and workflow as they related to work efficiency and infection control. Six of the 13 observed RNs agreed to be interviewed. Demographic data were collected at the start. Each interview session lasted 15 to 30 minutes and was conducted during normal work hours. An iPhone audio recording of each interview response was created. Three open-ended questions were asked: (1) What activities are usually done in the patient room? (2) How do you interact with the room environment and medical supplies and equipment when you deliver care in the patient room? (3) What are your opinions,

Table 1. Categories and Subcategories of Nursing Activities.

Nursing Activity Category	Nursing Activity Subcategory
Unit-related functions[a]	Unit-related functions
Nursing practice	Infection prevention procedures[b]
	Direct clinical patient care[c]
	Indirect patient care[d]
	Communication[e]
	Sampling blood for lab studies
	Documentation
Resource retrieval locations[f]	Around the bedside
	In the room (supply closet, nurse workstation)
	Outside of the room (medication room, tube system behind clerk's desk)

[a]Unit-related functions included preparing equipment and transporting patients between departments/rooms.
[b]Infection prevention procedures included hand hygiene, getting hand soap/paper towel, wearing personal protective equipment (PPE).
[c]Direct patient care included continuous monitoring of vital signs, observing the patient to evaluate their general condition, checking IVs (including checking the IV electronic readout, untangling IV lines), administering medication (including preparing medication), suctioning patient, cleaning patient, and comforting/playing with patients.
[d]Indirect patient care included picking up supplies/medication, retrieving soiled supplies and disposing of sharps, PPE, diapers and trash.
[e]Communication included communicating with other care providers and with family members.
[f]Resource retrieval locations referred to the locations of resources/supplies the nurses needed to retrieve during observed care delivery process.

desires, and expectations about a PICU patient room work zone of the future?

The audio interview content was transcribed digitally into a Microsoft Word document. The recording files were then deleted permanently to maintain RN confidentiality. All identifiers were eliminated from the transcription. The interview content was thematically analyzed and clustered by spatial area. RN responses were grouped as positive or negative and by common future expectations. Only data related to the work zone in the patient room were included. Information related to the family zone, bathrooms, televisions, and PICU operations was excluded from the analysis.

Results

Forty-eight observation sheets were completed in 35 hours of observing 13 RNs caring for 10 patients. In all, 539 RN clinical activities were documented, and a total of 156 surface contacts were recorded. Five areas of the patient room that most concerned RNs were identified. None of the observations was eliminated due to participant drop-out. Patient-specific electronic charting, nursing activities unrelated to patient care, and tasks performed outside the patient room were not recorded or included in the study.

Quantitative Measures

Six spaces identified by the SMM were patient bedside (left), patient bedside (right), disposal area, nurses' workstation, medication and supply preparation areas, and outside of the patient room.

Table 2 shows the RNs' movement frequencies between these areas during the 35 hr of observation. Most RN movements occurred between the bedsides (left and right) and the disposal area (25.9%, 68 times), the two sides of the patient bed (19.7%, 51 times), and the disposal area and the nurses' workstation (13.5%, 35 times). The frequency of movement between other functional spaces in the patient room comprised less than 10% of the total. The adjacency diagram generated for the traffic flow analysis (Figure 5) revealed that the highest walking frequencies occurred between the two sides of the bed and between the bedside area and the disposal area. These were designated the *immediate* adjacent level. The *general* adjacency and *near* levels

Table 2. Behavioral Mapping Traffic Flow Analysis.

From–To Zones Within Shared Patient Room Frequencies, *n* (%)	Bedside Left Zone	Bedside Right Zone	Disposal Area	Nurses' Workstation	Medication and Supply Area	Outside
Bedside left zone		51 (19.7%)	35 (13.5%)	21 (8.1%)	16 (6.2%)	1 (0.4%)
Bedside right zone			32 (12.4%)	20 (7.7%)	9 (3.5%)	2 (0.8%)
Disposal area				35 (13.5%)	9 (3.5%)	9 (3.5%)
Nurses' workstation					14 (5.4%)	4 (1.5%)
Medication and supply area						1 (0.4%)

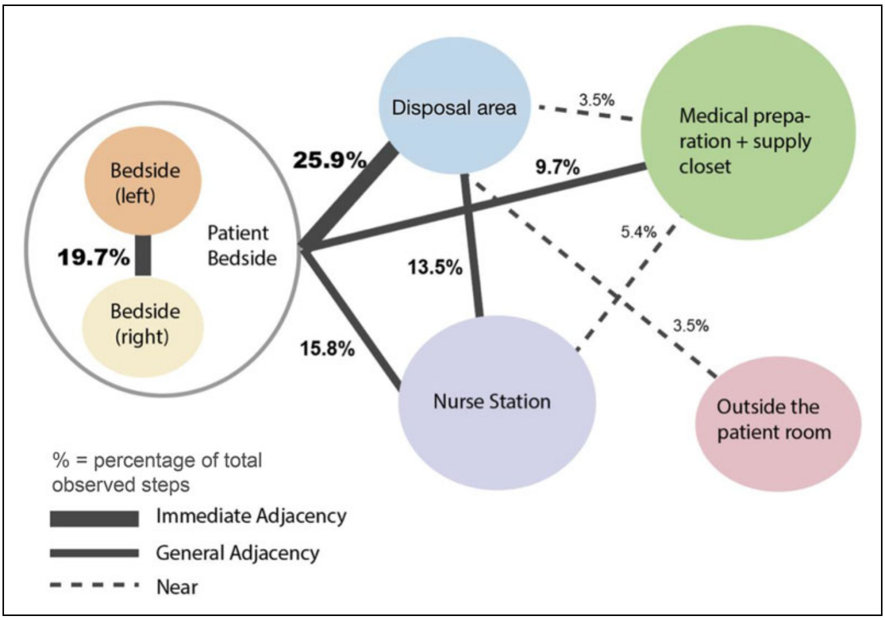

Figure 5. Traffic flow adjacency diagram.

of adjacency indicated that the current spatial layout supported RNs' work and did not add extra walking and inefficiency but could be further improved.

The breakdown of the 539 nursing activities as recorded by CAM is shown in Figure 6. Direct and indirect clinical patient care activities were performed with equal frequency: 164 times and 165 times, respectively. Figure 7 shows the frequencies of specific RN direct clinical care activities. The IV status was checked a total of 64 times (39%) during the observations. This activity included checking the IV electronic readout and untangling IV lines. Observing the patient to evaluate their general condition and vital signs was done 22 times (17%). Nearly half of the indirect patient care activities (47%) were spent on the disposal of waste, including sharps, supplies, personal protective equipment (PPE), diapers, and trash (Figure 8). RNs devoted similar numbers of activities to "picking up supplies/medication" (27%) and "retrieving trash" (26%).

A total of 156 contacts were recorded by the SCFM tool. Figure 9 summarizes the high-touch surfaces contacted during the observed care delivery process. The top four were (1) patient

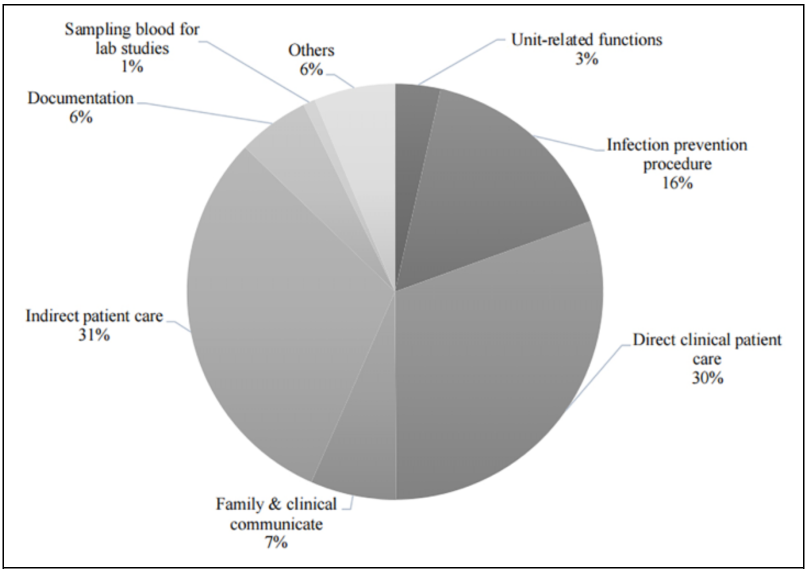

Figure 6. All clinical care performance breakdown.

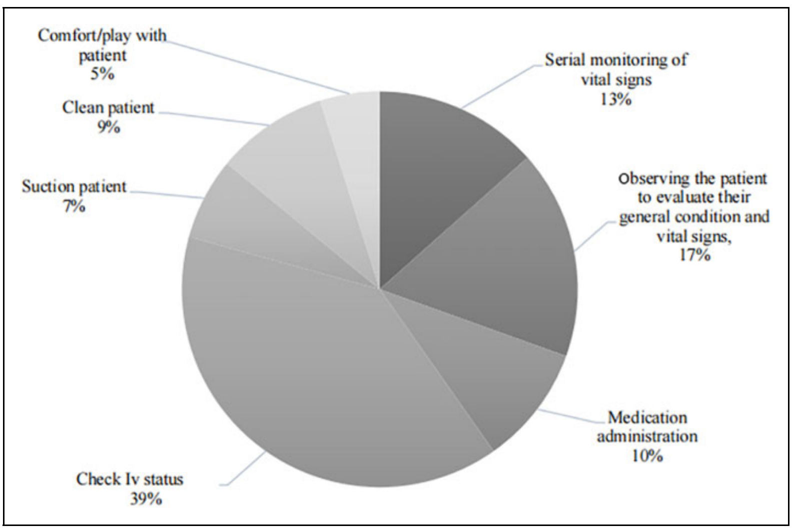

Figure 7. Direct clinical patient care breakdown.

bed rails, 63 times; (2) IV pumps and poles, 26 times; (3) tubing and medical equipment around the bedside, 23 times; (4) vital sign monitor screens, 20 times.

The association between RN workflow and contact with high-touch surfaces became evident after connecting the data from clinical activity mapping with that from the contact frequencies mapping. Direct patient care activities led to the most frequent contact with high-touch surfaces. Figure 10 shows the breakdown of nurse activities during which RNs touched the patient bed rails (63 times in total). These included checking IV status (13 times), cleaning patients (10 times) and suctioning patients (10 times). Checking the IV electronic readout (10 times) and untangling

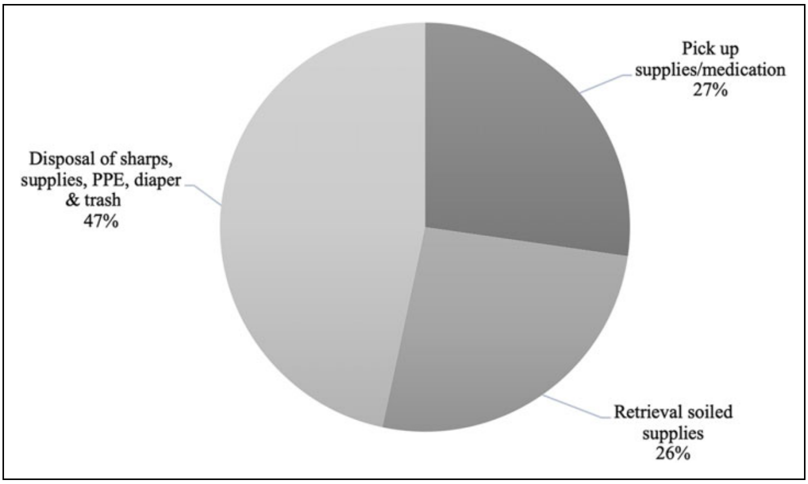

Figure 8. Indirect patient care breakdown.

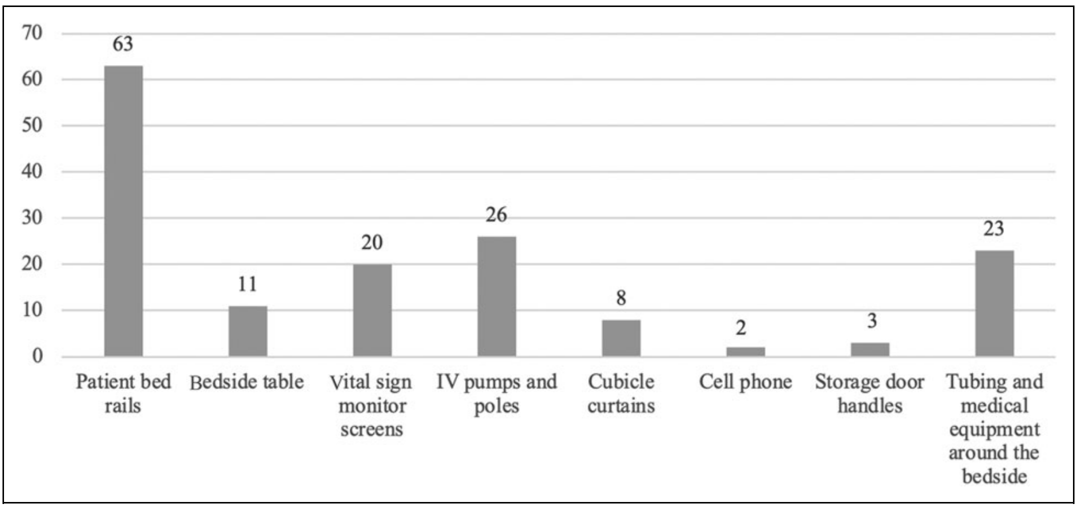

Figure 9. Frequency of high contact transmission surfaces.

IV tubing (5 times) were the two main activities in which RNs touched the IV pumps and poles (26 times). Tubing and medical equipment were the third most frequently contacted surfaces (23 times) during direct patient care (Figure 11). Activities included untangling IV lines (6 times) and continuous monitoring of vital signs (2 times).

Qualitative Measures

The analysis of RN interview responses identified five areas of concern: nurse workstation, supply retrieval/disposal, sink, bedside work zone, and vital sign monitor. Positive and negative feedback on the current conditions and expectations for the future included: (1) Locating the nurse workstation inside the patient room saves them walking during patient monitoring and care delivery. However, the individual workspace is not large enough and always cluttered with charts, PPE, and personal items (RN, interview, November 14, 2018). (2) Locating the supply closet in the patient room, not far from the patient's bedside, improves workflow. One RN described how the

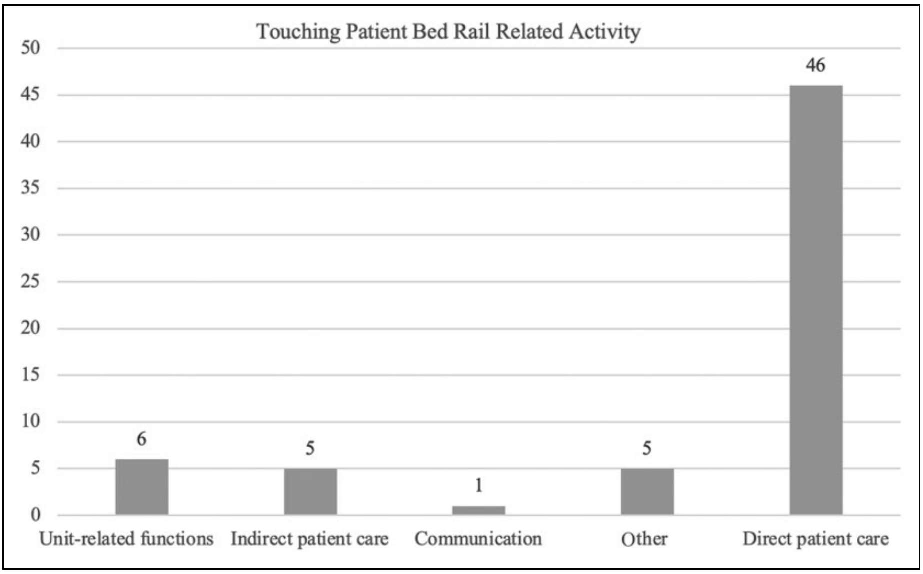

Figure 10. Registered nurses' activities associated with contacting patient bed rails.

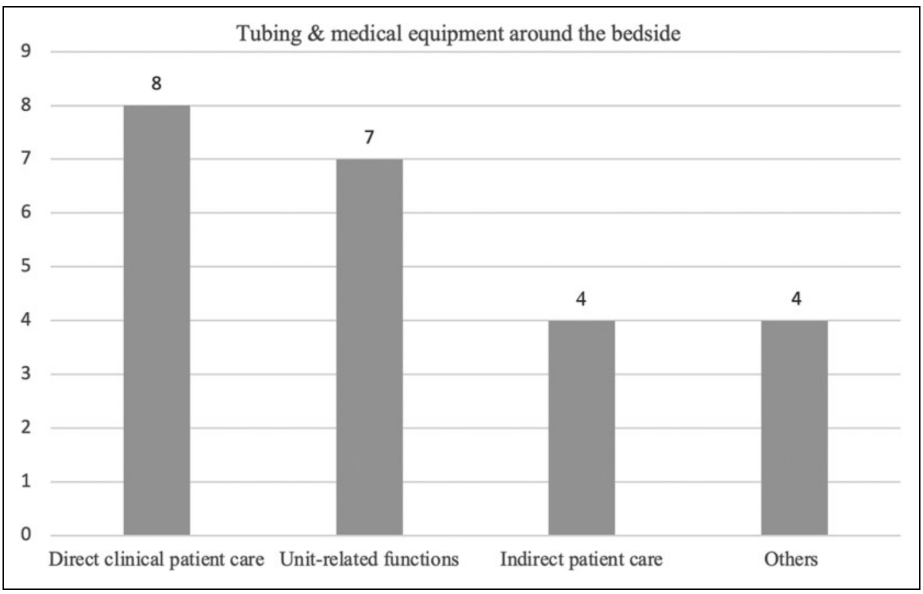

Figure 11. Registered nurses' activities associated with contacting bedside tubing and medical equipment.

current disposal area could be enhanced to save time and activities: "...if you are changing a diaper and using other material that is the garbage, you would pile them on the bed, and then bring it together to the garbage. It would be probably helpful if there is a garbage can closer to the bedside" (RN, interview, November 13, 2018). (3) The centralized sink is located at the back of the nurse station and next to the medication preparation area in every patient room, which reduce unnecessary walking for RNs. The current layout could potentially foster cross-contamination as “random people come and use the sink while passing by my preparation area, which is not ideal” (RN, interview, November 13, 2018). (4) Interviews highlighted the lack of adequate space around the bedside for the clinical activities performed in these zones. One RN responded, “I put myself in danger trying to plug things in and take them out like where I could trip and get caught in my patient’s tubing and then harm them . . . we do end up putting [supplies] on the bedside table . . . ” (RN, interview, November 14, 2018). (5) Comments about the vital sign monitor revealed that the current monitoring system and arrangement in the room hindered RN work efficiency and led to higher frequencies of contact with the monitor screens. “A lot of times the alarm beeps, so every time you either have to walk over there, or we have these remotes, but these remotes always do not work” (RN, interview, November 12, 2018).

RN feedback on the ideal patient room work environment of the future is elaborated on in the design guidelines in the Discussion section.

Discussion

By comparing and analyzing the results of the SMM, CAM, SCFM, and interviews, our study demonstrated the effect of the physical environment in the PICU patient room on RN work efficiency and safety. Our study confirmed the finding in Hendrich’s (2008) study that 50% of an RN’s time is allocated to direct patient care. Of the workflow activities dedicated to direct patient care, 27% were to access equipment and supplies. These are considered non-value-added activities and should be minimized. RNs’ frequent trips between clean and soiled areas, imposed by the spatial arrangement, is a preventable vector for infection transmission in SFRs and OB room configurations. The surfaces most frequently touched in our study, which by evidence correlate with highest risk of transmission, were in the bedside work zone: (1) patient bed rails, (2) IV pumps and poles, (3) extension tubing and medical equipment, and (4) vital sign monitor screens. A summary of our key findings and proposed solutions can be found in Table 3.

Three major areas in the patient room could be improved by designing them to reduce unnecessary activities while the RN is providing care. First, providing sufficient walking space around the head of the patient bed would allow RNs to gain easy access to all the equipment needed (Figures 12 and 13). The traffic flow analysis showed a high frequency of RN movement between the two sides of the patient bed while conducting direct clinical patient care activities, which are considered value-added activities. However, RNs reported extra walking around the bed to adjust IV lines, check the monitor, and operate equipment, all of which are considered non-value-added work (Liker, 2003). Prior studies also indicated that lack of space around the bedside can hinder the RN workflow, reduce work efficiency, and increase physical effort (Lavender et al., 2015; Thompson et al., 2012). Providing a ceiling-mounted flexible beam for outlets and permanent equipment that can be rotated and easily moved around the patient bed (Figure 12) would add space for work, reduce unnecessary walking between the two bed sides, and minimize visual clutter (Thompson et al., 2012). The equipment should be designed using an artistic, child-friendly theme, similar to what has been done in magnetic resonance imaging (MRI) suites, with childproof safety covers that hide tubing and wires, to address patients’ emotional, social, and developmental needs (Meert et al., 2013; Ulrich et al., 2008).

Designating a trash zone would also reduce wasted activities and improve infection prevention. Traffic flow analysis revealed a high frequency of movement between the patient bedside and the disposal area, highlighting the importance of the space adjacency between these two areas. The majority of RNs’ activities between these two areas were spent on indirect patient care activities: disposing of sharps, supplies, PPE, diapers, and trash, which are all considered non-value added. In a study of 10,000 RNs working in adult hospitals in Pennsylvania, 34.3% of them reported spending a significant portion of their time performing housekeeping duties, including disposing of trash (Aiken,

Table 3. Summary of Key Implications.

Topics	Key Observations	Implied Solutions
Work efficiency	• Heavy traffic flow between two sides of the patient bedside • Heavy traffic flow between the bedside and the disposal area • Large percentage of RNs' direct clinical patient care activities spent on checking and unalarming vital sign monitors and IV pumps. • Large percentage of RNs' indirect patient care activities spent on disposing trash, diapers, sharps, and PPE. • RNs reported that they need more walking space and work surfaces around the bedside to reduce inefficiency and hazards to patients' safety.	• Providing sufficient walking space around the patient bed • Providing ceiling mounted flexible beams • Providing designated trash zone • Positioning decentralized and easily accessible supply stations • Facilitating line of sight to the vital sign monitors
Infection prevention: Contact transmission	• Four highest possibilities of contact transmission surfaces: patient bed rails, IV pumps and poles, tubing and medical equipment around the bedside, and vital sign monitor screens. • Privacy curtain and over-bed patient table are the fifth and sixth high contact surfaces in the patient room that are constantly touched by not only RNs but also families, visitors, and staff. • Current workflow adds RNs' contact frequencies with identified surfaces in the patient room.	• Reducing pathogen density on high-touch surfaces with frequent cleaning or use of antimicrobial materials for these surfaces. • Facilitating access to sinks and alcohol-rub dispensers. • Directing movement flow from clean to dirty.

Note: PPE = personal protective equipment; RNs = registered nurses.

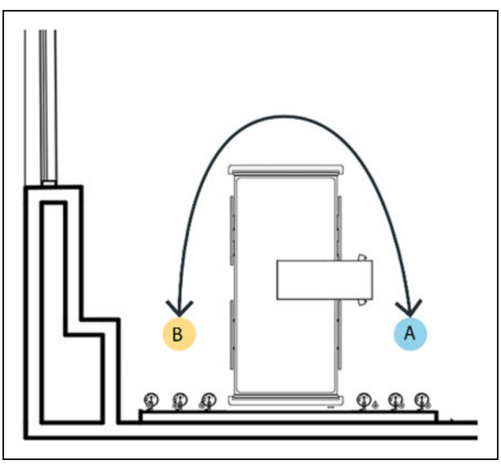

Figure 12. Current workflow around the bedside.

2002). RNs in our study also reported that they devoted extra effort disposing of the trash after the care delivery process. Increasing the visibility of contaminated and clean zones would help to restrict healthcare workers' (HCWs') movement, thereby limiting the potential for contamination (Herlihey et al., 2017). Color coding on the floor or wall would restrict traffic between the sterile and contaminated zones (Gurses & Carayon, 2007). The trash bin could be kept from overflowing by placing it near the room's entrance for convenient collection by housekeeping.

The adjacency diagram suggests that immediate adjacency is required between the nurse workstation and the medication preparation area. Therefore, decentralized, easily accessible

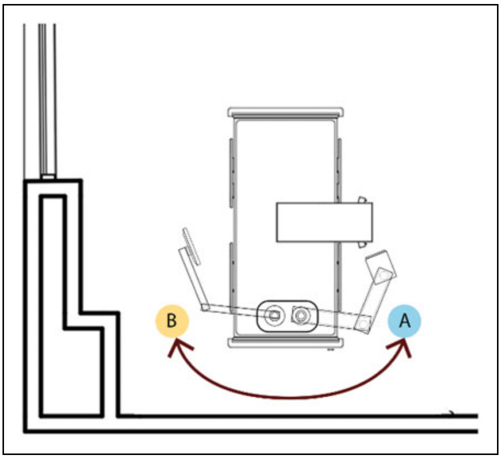

Figure 13. Proposed workflow around the bedside with ceiling-mounted beam arms.

patient-specific supply cabinets should be located near the point of care. Extra walking to pick up supplies and medication and to don and doff PPE wastes time, delays patient care, increases RN frustration, and decreases quality of care (Rathert et al., 2006; Tucker & Spear, 2006). In our study unit, the lack of an easily accessible, predesigned location for PPE left it scattered around the nurse workstation, where it could be subjected to unnecessary handling and cross-contamination, and obstruct nurses' view of the patient bedside. As supported by past research, decentralized supply areas improve work efficiency and reduce walking distance (Hendrich, 2008; Shepley & Davies, 2003). Pass-through cabinetry, accessible from inside the room and from the corridor, organized into patient-specific sections to prevent cross-contamination, can be installed to further enhance efficiency. The most frequently used items can be placed on top, with a patient-specific medication cabinet below it for ready access. Keeping frequently used supplies in a patient-specific cart within easy reach of the patient bedside obviates the need for nurses to hunt down supplies from the more distant central supply area and reduces the potential for cross-contamination. Smaller PPE organizers and a smaller trash bin could be placed around the bedside; the latter positioned outside the clean zone and free from obstruction, for the removal of smaller items such as gloves (Thompson et al., 2012).

Extra walking to pick up supplies and medication and to don and doff PPE wastes time, delays patient care, increases RN frustration, and decreases quality of care.

An unobstructed line of sight to the patient vital sign monitor screen from the nurses' workstation and around the patient care areas is required when caring for critically ill children. A screen at the nurses' workstation that would enable simultaneous monitoring of all three patients would reduce extra walking to check vitals and silence monitor alarms. Alarms are sensory distractors that hinder HCWs' efficiency (Ulrich et al., 2008), and silencing them is non-value-added work. Introducing a central vital sign monitor screen with remote controllers or a portable iPad device with readouts for all patients in the room would enable RNs to quickly silence the alarms and recognize changes in patient vitals sooner, thereby enhancing care quality and potentially improving outcomes.

Our study found a relationship between RN workflow and frequency of contact with specific surfaces in the patient room, namely the patient bed rails, IV pumps and poles, tubing and medical equipment, and vital sign monitor screens. Huslage et al. (2010) made a similar observation; their study rated the bed rail, IV pump, monitor, IV tubing and monitor cables as the top high-contact surfaces of the 28 common surfaces in intensive care units. In our study, the over-bed table and the privacy curtain were the fifth and sixth most frequently contacted surfaces. They are prone to contact not only by RNs but also by other HCWs, patients, families, and visitors (Dancer et al., 2009). Facility layout, equipment placement, and design affect RN movement flow in the space and directly impact infection prevention compliance (Anderson et al., 2010; Cohen et al., 2014).

Facility layout, equipment placement, and design affect RN movement flow in the space and directly impact infection prevention compliance.

Frequent cleaning and the use of antimicrobial materials reduce pathogen density on high-touch

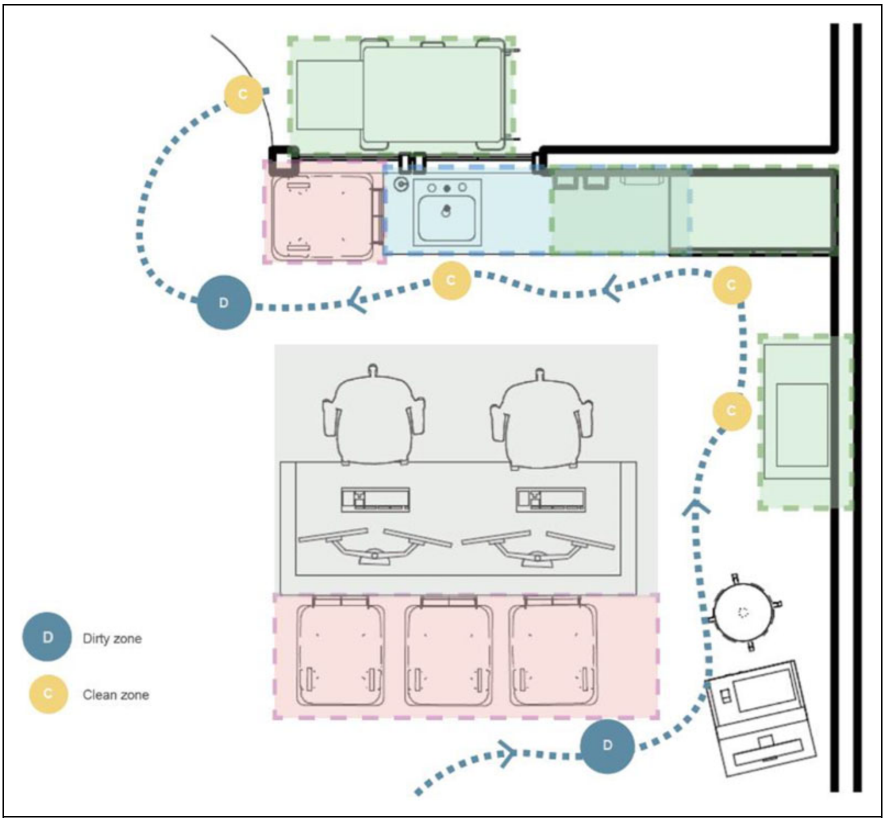

Figure 14. Current workflow in the communal work zone.

surfaces and decrease infection transmission. Schmidt et al. (2012) found that copper surfaces, compared to standard surfaces, resulted in an 83% reduction in bioburden. According to Salgado et al. (2013), the proportion of patients developing HAIs was decreased by nearly half to 56% in ICU rooms with copper surfaces compared with standard rooms. Inorganic metals and polycationic surfaces are also effective alternatives for reducing HAIs (Klibanov, 2007; Stobie et al., 2010). Light-activated antimicrobial materials can be used for tubing, wires, and finish coatings to reduce pathogens. Photosensitizer-containing coatings and medical-grade silicone that is infused with crystal violet, methylene blue, and gold nanoparticles have strong antimicrobial activity under both white light and dark conditions (Noimark et al., 2014). In units such as the one where our study was conducted, replacing the current privacy curtains with easily washable, copper-infused materials would be a simple and cost-effective intervention that would reduce the patient's and RN's exposure to the resistant pathogens in the ICU.

Positioning sinks and alcohol-rub dispensers in locations that are easily accessible from medication preparation areas and the patient bedside will improve RN hand hygiene compliance. Multiple studies pinpoint hand hygiene as an essential intervention for reducing contact-associated infection (Boyce & Pittet, 2002; Pittet et al., 2006). Bischoff and colleagues (2000) found that accessible bedside hand sanitizer dispensers could not only improve hand hygiene compliance but also reduce bacterial load, thereby decreasing the cross-contamination and HAIs. Strategic positioning of the dispensers also enhances provider efficiency by reducing non-value-added activities.

Directing movement flow in the communal work zone from clean to dirty optimizes RN

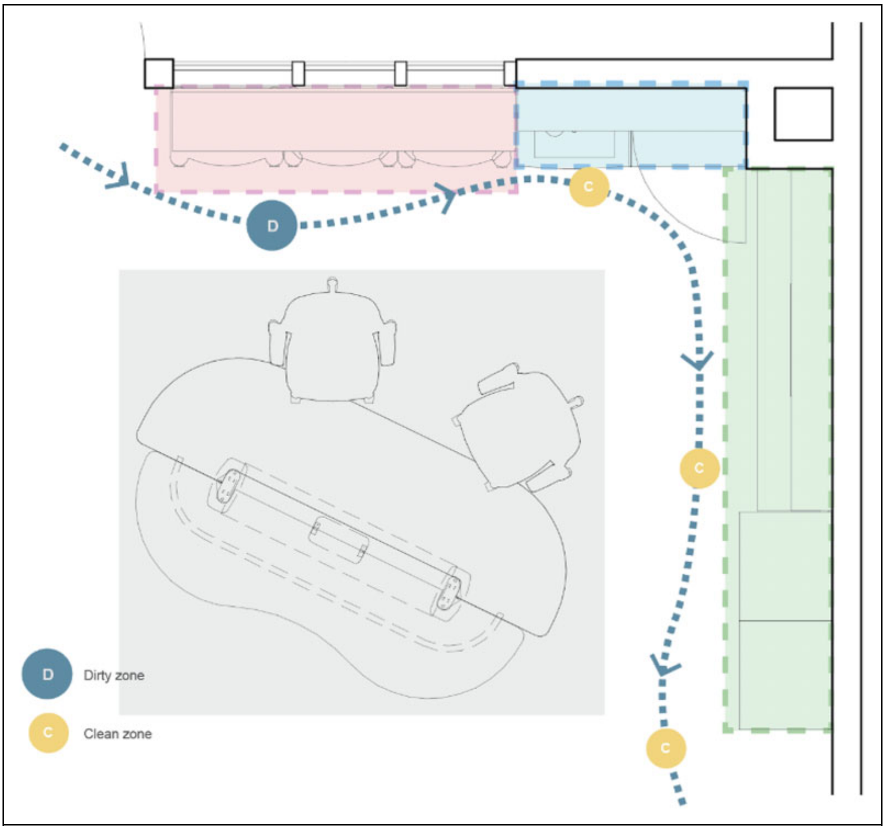

Figure 15. Proposed clean-to-dirty workflow in the communal work zone (Hor et al., 2016).

workflow and minimizes cross-contamination (Figures 14 and 15). Moving from clean (protected from pathogens) to contaminated areas prevents transmission of pathogens, while moving in the reverse direction requires additional cleaning and relocating of the sink, hand sanitizer dispensers, and PPE storage to reduce bioburden (Hor et al., 2016). As shown in Figure 15, locating the sink and PPE storage next to the trash bins ensures infection prevention for both circulation directions.

Incorporating a thorough room-cleaning checklist into the infection prevention protocol that focuses on the top six high-contact surfaces and the areas that are frequently overlooked decreases contact-transmission-associated infection (Hung et al., 2020; Rock et al., 2016). In their 2008 study, Carling et al. found that less than 50% of surfaces were cleaned during terminal cleaning of the patient room (after the patient is discharged). Ideally all environmental surfaces in an ICU should be disinfected (Carling et al., 2008). Current evidence suggests that this seldom occurs.

Finally, while the current study was conducted before the onset of the COVID-19 pandemic, the issues we've raised have only been magnified during this widespread infectious disease outbreak. The complex and demanding nature of optimal critical care delivery requires focus, attention, and synchrony, and leaves little room for error. The increased risk of HAIs, greatly increased workload, frequent understaffing due to illness, and exponential rise in work-related stress (Baccolini et al., 2021; Balistreri et al., 2021) placed undue burdens on HCWs already struggling with burnout. Scores of RNs, who were ill-prepared for the PPE and supply shortages, care-rationing, and frequent, unexpected deaths, experienced a sense of helplessness that was especially damaging, given the extent to which their professional and personal identities are shaped by their competence and self-reliance. The need to perform duties beyond their scope of practice in the unfamiliar environment of a repurposed operating room or clinic superseded the "person–environment fit" (Tinsley, 2000) that ensures the psychological well-being required to adapt to the frequent changes and function at a high level during an evolving crisis. At best these conditions are a distraction that must be recognized and responded to, but at their worst, they pose an added threat to the safety and well-being of workers and patients alike, and demand additional safeguards against adverse events.

Limitations

This case study was limited to a PICU in one urban hospital, and the observation was conducted in only one of four identical triple-patient rooms. Expanding our study to include additional ICUs in the same hospital, other PICUs in the same city, and PICUs in other cities would help to establish the generalizability of our findings. Although evidence-based, our three-part assessment tool has not been validated using an existing standard for workflow efficiency. In addition, so as not to disrupt their work schedules, and to accommodate their limited availability, only six nurses could be interviewed. No observations or interviews were conducted during overnight hours. The perspectives on care delivery and suggestions for improvement offered by night-shift nurses may differ from those who work predominantly during day shifts, and key findings may have been missed. Finally, interviewing families to gain their perspective on RNs' behaviors and attitudes towards their work would have added another dimension and enriched the study results.

Conclusion

Complex work environments like the PICU present unique challenges to providers committed to delivering high-quality, efficient, and safe care. Likewise, the designer focused on optimizing workflow efficiency and safety must recognize the constraints within the medical ecosystem. It is essential in such environments that the design and human factors are aligned with and optimized for the clinical activities and treatment goals.

Person–environment interaction analysis using our tool offers valuable insights that can be used for design enhancement. Understanding RN workflow and contact transmission risk and applying that knowledge to the layout of the therapeutic environment will improve the workspace for RNs and has the potential to positively impact outcomes for patients and their families.

Future Research

Our future research will evaluate the impact our design recommendations on RN work efficiency, safety, and infection transmission, using the current study as a baseline, in a pre–post study design.

Implications for Practice

- We present a novel visual tool designed to help identify the impact of the physical environment in the pediatric intensive care unit patient room on staff work efficiency and hospital-acquired infections.
- Evidence-based design guidelines that enhance workflow and reduce contact transmission of pathogens are proposed.
- The application of our model to address the challenges presented by multi-bedded patient rooms is discussed, along with proposed solutions.

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ORCID iD

Yuqian Lu, MA https://orcid.org/0000-0003-2815-6210

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