Title of Project: Realizing Improved Patient Care through Human-centered Design in the OR (RIPCHD.OR)

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The PSLL allowed the RIPCHD.OR team to mobilize the expertise of this incredible multidisciplinary group of experts, faculty, and students to understand the OR work system in greater depth than has been attempted previously. Further, the systems engineering framework of the PSLL facilitated the transition from understanding to design innovation and implementation. The RIPCHD.OR team is extremely grateful to AHRQ for this incredible opportunity and for developing the vision for this PSLL grant mechanism. This project is truly the result of the tireless effort and support of so many beyond the RIPCHD.OR research team and collaborators. This includes the leadership at both universities, grants management teams, financial and administrative teams, colleagues, friends, and families.

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1. Structured Abstract

a. Purpose

The purpose of this project was to use a systems engineering approach to develop ergonomic and safe operating room (OR) design solutions that improve staff workflow and perioperative outcomes.

b. Scope

The operating room is a very high-risk, problem-prone patient care environment. Surgical site infections and errors are key concerns in ORs. Distractions and interruptions are major causes of medical errors during surgery. The wide range of equipment used to perform procedures, rapidly changing technology, and the physical space where care is provided pose challenges to providing high-quality care.

c. Methods

Video observation and coding, bacterial load analysis, interviews, and focus groups were used during problem analysis. Simulation-based evaluation was used to iteratively evaluate design ideas and prototypes. Elements of the RIPCHD.OR prototype were implemented in MUSC's new R. Keith Summey Pavilion in Charleston, SC. The RIPCHD.OR team conducted a post-occupancy evaluation using video observations and interviews in late 2019 and early 2020.

d. Results

The project found that operating room size, room design, and layout may create barriers to task performance, potentially contributing to the escalation of disruptions and errors in the OR. RIPCHD.OR resulted in the design of a safer and more efficient OR prototype, 22 peer-reviewed publications, more than 60 conference presentations, and a web-based safe OR design tool. The post-occupancy evaluation of the new pediatric ASC demonstrated a reduction in disruptions and improved utilization of OR space.

e. Key Words: operating room, systems engineering, patient safety, simulation

2. Purpose

The Realizing Improved Patient Care through Human-centered Design in the OR (RIPCHD.OR) patient safety learning lab (PSLL) was set up to create a strong multidisciplinary network of people and places that together could effectively address patient safety issues in the OR. The RIPCHD.OR project used a multidisciplinary, human-centered systems approach to incorporate evidence-based design, human factors, and systems engineering principles to design a safer, more ergonomic operating room (OR). A multidisciplinary group of core team members, advisory committee members, and user groups was actively involved throughout the project to support the goal of designing an OR that addresses patient and staff safety issues in this high-risk--prone environment.

The specific aims of this patient safety learning lab were:

Specific aim 1: Formally structure the RIPCHD.OR learning lab and establish laboratory infrastructure and team management.

Specific aim 2: Develop a systematic approach to evaluating the impact of people, tasks, tools, and technology and the built environment in developing ergonomic and human-centered OR design solutions.

Specific aim 3: Develop process design recommendations to support key OR flows (OR team members, supplies, patient, equipment, information) that impact patient safety outcomes, such as surgical site infections and surgical errors.

Specific aim 4: Develop evidence and recommendations related to the use of advanced displays and multimodal displays for anesthesia tasks to mitigate the masking of important signals.

Specific aim 5: Develop an evidence-based framework and methodology for designing operating rooms that achieves the desired patient and staff safety outcomes. This component of the study aimed to integrate the findings and recommendations from all proposed aims.

3. Scope

The incidence of adverse events, such as surgical site infections and surgical errors, is an immense problem in the OR. Two to five percent of all patients who undergo an operation will develop a surgical site infection, leading to significant mortality and morbidity. Distractions and interruptions are major causes of medical errors during surgery. Previous attempts to reduce adverse events in the OR have focused on enhancing skills and training for the clinicians involved in the direct care of the patient. However, little effort has been directed at the environment within which healthcare providers work. Research in complex settings suggests that adverse events are often caused by a combination of active and latent failures (inherent in the system), and interventions that target these systemic factors are often more efficacious than approaches that focus exclusively on individual characteristics.

The operating room is a very high-risk, problem-prone patient care environment. The dynamic medical technology and clinical practice in the operating room have been changing rapidly. Increasingly, diagnostic and imaging capabilities are being incorporated in the surgical domain, and procedures and surgical practices are transitioning from mostly open procedures to techniques that are less invasive and more equipment intensive. There are many new players and subspecialties involved in providing care in the operating room. The use of a range of equipment and technology places varying demands on building systems and space requirements. Patients are highly vulnerable in this setting.

Environmental sources of disruption in the OR include frequent door openings, loud noises and alarms, environmental clutter, and constrained spaces. Coupling small and cluttered ORs with high foot traffic inside the OR as well as movement in and out of the room may contribute to flow disruptions (e.g., people or equipment blocking visibility and communication between surgical team members) and increase infection risks (e.g., nonsterile surgical personnel bumping into a sterile instrument table). Additionally, poorly organized storage spaces and the lack of proximity between key functional areas can result in unnecessary travel and time wasted during surgical procedures, ultimately causing delays and adding costs to healthcare organizations.

The RIPCHD.OR PSLL team focused on operating rooms for ambulatory pediatric surgery and for adult orthopedic surgeries, because the Medical University of South Carolina planned to build two new ambulatory surgery centers dedicated to these two specialties between 2016 and 2018. There was a unique opportunity not only to conduct research related to patient safety and workflow for these surgical areas but also to develop solutions that can be implemented in a live facility. The project focused on surgical teams working in outpatient pediatric ORs and adult orthopedic ORs. Surgeons, anesthesia providers, nurses, and techs were involved throughout the project and actively contributed during the design process. Although patients were included in the surgery observations, they were not included in the design process.

A multidisciplinary team from Clemson University (Architecture, Industrial Engineering, and Business departments) and the Medical University of South Carolina (anesthesia providers, surgeons, and nurses) partnered with architects and industry experts to study, design, develop, and implement human-centered design concepts in the operating room.

4. Methods

The RIPCHD.OR PSLL used a human-centered systems engineering approach to address the specific aims of this learning lab. The methods used to address the four key stages of this systems engineering approach – problem analysis, design and development, implementation, and evaluation – are summarized here:

Problem analysis

Literature Review

The RIPCHD.OR team kicked off the project with a review of 198 articles, which helped identify key categories of OR outcomes (e.g., disruptions, errors, satisfaction, infections) and design factors impacting those outcomes (e.g., air quality, acoustics, lighting, materials, layout, visibility). This literature review, published in HERD journal (Joseph et al., 2017), helped focus data collection efforts for the team, providing structure to the video observations and case studies being conducted.

Video Observations and Coding

Using a human factors framework (Systems Engineering Initiative for Patient Safety 2.0 – SEIPS 2.0, by Holden et al., 2013), the research team observed 35 surgeries (primarily pediatric and orthopedic outpatient procedures) conducted in five different ORs at MUSC. Video cameras installed in four corners of each OR unobtrusively collected videos of all stages of the procedure (preoperative, intraoperative, postoperative, turnaround). A coding software (Noldus Observer®) and a coding protocol developed in a previous study (Palmer et al., 2013) and expanded upon in the current project were used by trained researchers to code the type, location, and duration of surgical flow disruptions and activities performed by key surgical team members (e.g., circulating nurses, scrub nurses, surgeons, and anesthesia providers) and objects (e.g., instrument tables) in each surgery. Door openings and surgery phases were also recorded.

To optimize coding and make results more meaningful, each OR was organized into location zones based on the primary functions within each zone (e.g., surgical table zone, circulating nurse workstation zone, supply zone), and activities performed by team members were categorized as patient, equipment, materials and supplies, and information related (PEMSI). Flow disruptions were categorized as they related to layout (inadequate use of space, impeded visibility, connector positioning or furniture positioning hindering the surgical team from performing their tasks), environmental hazards (e.g., objects causing collision/bumping or the risk of slipping/falling/tripping), usability (e.g., malfunctioning furniture and equipment), equipment failure, and interruptions (e.g., surgical team members spilling/dropping/picking up items or searching for missing surgical items). Moreover, flow disruptions were also coded in terms of their severity (from no/minor impact to momentary distraction, disruption, and repeated task). The event-based data obtained from the Noldus Observer XT12 was transformed into time-based data that allowed a range of different types of analyses to understand workflow patterns and disruptions experienced by surgical team members.

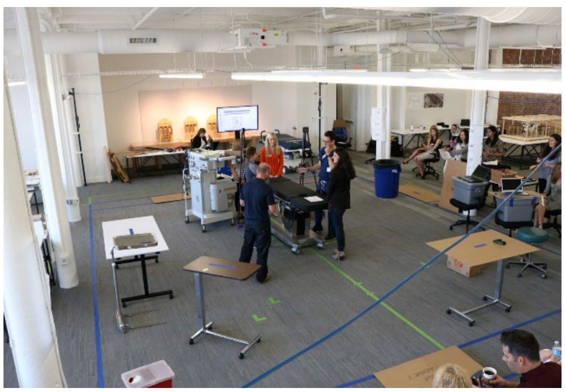
Case Studies and Flow Mapping
In order to more deeply investigate best practices in OR design across the United States, the research team visited three surgical facilities with varying spatial configurations and operational models in addition to the study sites at MUSC. The goal was not only to learn lessons about design- and technology-related facilitators and barriers within the OR but also to gain insight into spaces and workflows around the OR that potentially impact the outcomes of the surgical procedure. To meet these goals, the research team developed a case study tour protocol that included a flow mapping tool (Machry et al., 2021) focused on documenting and evaluating eight different types of flows within the surgical unit (patient, family, surgeon, anesthesiologist, instruments/materials, supplies, movable equipment, and waste) and how discrete steps within these flows may be impacted by the spatial configuration. The tool guided interviews with stakeholders, the development of flow diagrams, and a process-based spatial evaluation framework focused on efficiency. Spaces used for traveling (e.g., elevators and corridors) or storage, for instance, were evaluated as to whether they were likely to present risks of delay to the next surgical case in the form of bottlenecks and/or longer distances from one step to the next.

Design and Development
Data from the literature review, observations, and case studies were used to develop several OR design alternatives while also informing multiple data analysis strategies, such as spaghetti diagrams and discrete-event simulation models created to better understand flow patterns in the OR. The OR prototype was refined through several stages of simulation-based mock-up evaluations with end users (surgical team members), iteratively refining the OR prototype toward its final version. The final OR prototype was then evaluated via high-fidelity simulations of surgical procedures in the physical mock-up as well as by a computer-based simulation approach (proactive modeling) testing different versions of the prototype (different room size, shape, and layout) against traffic flow patterns obtained from observations.

Development and Simulations of OR Prototype and Mock-ups
The final OR prototype and high-fidelity mock-up resulted from four intense cycles of design-fabrication-testing-redesign in a process involving the cross-disciplinary research team, an

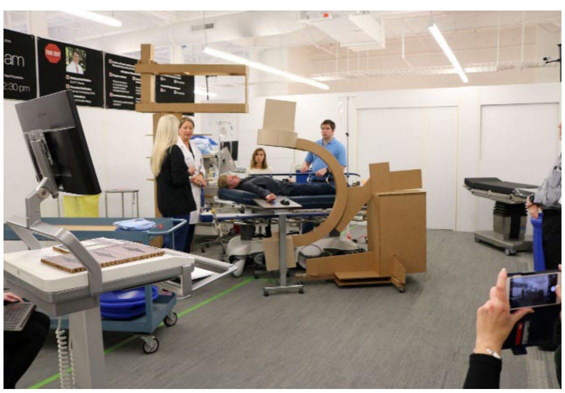
advisory committee, the architecture firm working on the new ASC project, and graduate students. The initial task was to build collectively an evidence-based framework to guide the design of the prototype. This was done based on the literature review and workshops bringing the entire team together to filter evidence and best practices relevant to the project. After reaching consensus and clarity on the design vision and guidelines, several design solutions were developed, narrowed down, and replicated in a low-fidelity tape-on-the-floor mock-up.

Flexible enough to reflect various design alternatives, the first tape-on-the-floor mock-up was tested through a set of simulations with surgical team members (pediatric and orthopedic) to refine the design. This mock-up confirmed basic room floor area and dimensions. It also tested several potential door locations. As depicted in Figure 1, this process was repeated two more times with cardboard mock-ups, allowing for a dramatic reduction in the number of design alternatives being tested each time and ultimately leading to the development of the final version of the prototype to be reproduced in a high-fidelity mock-up with real walls and surgical equipment.



Mock-up 1: Tape on floor (low-fidelity)

Mock-up 2: Cardboard (level 1)



Mock-up 3: Cardboard (level 2)

Mock-up 4: Real walls and equipment (high-fidelity)

Figure 1: Four stages of mock-up development.

Structured around the prototype design and mock-up fabrication, simulation scenarios were developed to test OR design alternatives in each stage described above, with simulation results informing the redesign of the prototype in the next stage. The RIPCHD.OR team developed a simulation-based evaluation toolkit with simulation scenarios and protocols that were tailored to test different design alternatives (Bayramzadeh, Joseph, Allison, et al., 2018). Scenarios depicted different types of ambulatory surgery procedures (pediatric and orthopedic surgeries), surgery phases (preoperative, perioperative, postoperative, and turnaround phases), and OR configurations (e.g., with one or two doors; with or without adjacent rooms, such as the induction room). Always including end users (e.g., surgeons and nurses), the toolkit defined a simulation director, participant roles and tasks, equipment and tools involved, and a simulation schedule involving a sequence of discrete/shorter simulations (e.g., patient bed entry/ exit sequences). Each simulation was immediately followed by debriefings and focus groups to discuss perceptions and lessons learned from the simulation.

Implementation and Evaluation

Computer-based Simulations of the OR Prototype

Once the final design of the OR prototype was defined and built in the high-fidelity mock-up, a digital simulation method was deployed to manipulate various features (size, shape, and layout) and test their performance against the flow patterns obtained from coding video observations of actual surgeries. As explained in detail in other publications (Taaffe et al., 2020; Khoshkenar et al., 2017), a computer-based simulation modeling approach was created to simulate these flow patterns in the different versions of the OR prototype (Figure 2). Different OR sizes (421, 579, and 739 square feet or approximately 39, 54, and 68 square meters), shapes (square and rectangle), and layouts (surgical table positioned perpendicularly or angled to the OR walls) were compared to see how they performed in terms of flow measures impacting safety and efficiency during surgery – the number of contacts between people/ equipment, the distance traveled by surgical team members, and the number of transitions near the surgical table area.

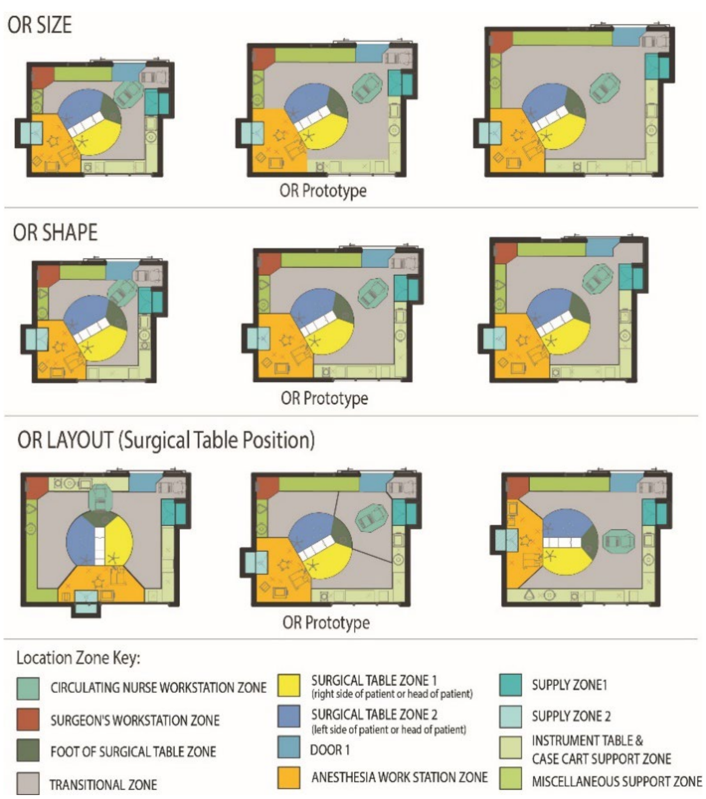


Figure 2: Manipulations of the OR prototype in terms of size, shape, and layout that were tested against proactive simulations of flow patterns.

Safe OR Design Tool

An interactive, web-based tool was developed based on the literature review and key findings from the different phases of the RIPCHD.OR project. The purpose of the Safe OR Design Tool is to support clinicians, designers, and researchers in better understanding how to design a safer and more ergonomic OR. Project teams worked closely during content development to ensure the information disseminated through the tool is a comprehensive representation of the RIPCHD.OR project as a whole. The Safe OR Design Tool was developed using a systems approach that provides design strategies related to desired safety outcomes. The tool creation process included the development of evidence-based design strategies linked to design features (e.g., booms, layout), desired outcomes (e.g., improve movement and flow), and systems components impacted (e.g., people, built environment, tools). The content for the tool was reviewed by a panel of experts in OR design. Through a modified Delphi process, 16 experts iteratively evaluated the proposed content until consensus was reached regarding the final comprehensive set of design strategies. In addition to developing the content for the Safe OR design tool, the web interface was developed simultaneously and tested with users.

Post-occupancy Evaluation (POE)
In December 2019, the RIPCHD.OR team visited the new pediatric Ambulatory Surgery Center (ASC) at the Medical University of South Carolina (MUSC) in Charleston to conduct a post-occupancy evaluation (POE) of the operating rooms. A POE toolkit was developed specifically for this evaluation. The POE included 1) conducting observations to map out key flows, layouts, and locations within the facility; 2) conducting interviews with nurses, anesthesiologists, surgeons, and techs; and 3) setting up the process of collecting video recordings of surgeries performed at the new MUSC pediatric ASC. Video recordings of the ORs were collected over several weeks to obtain a variety of surgery types. The videos of the 25 surgeries, flow maps, pictures, and interviews were then analyzed to understand the impact of OR design and induction rooms on staff workflow and to identify design barriers and facilitators.

5. Results
The RIPCHD.OR PSLL resulted in 22 peer-reviewed publications, a high-fidelity OR prototype, implementation in a new surgery center, and a web-based OR design tool. The findings from the individual research studies informed the key products from this study and are incorporated within the narrative provided here. The complete list of publications is also provided.

Evidence-based OR Design Prototype
OR Design Guidelines
A major outcome from the initial phases of this research (literature review, video observations, and brainstorming workshops) is the confirmation of a project vision and a series of evidence-based design goals and guidelines. A set of five evidence-based goals – 1) optimize operational efficiency and effectiveness; 2) optimize clinical outcomes, health, and safety; 3) optimize the experience for both patients and staff; 4) optimize green and sustainable practices; and 5) optimize the ability to accommodate changing needs over time – led to a series of nine inter-related OR design guidelines: optimize movement and processes, maximize visual awareness, integrate information display, minimize institutional clutter, minimize surface and airborne contamination, control access to daylight and appropriate artificial lighting for the range of activities in the OR, and employ a flexible room/suite chassis with flexible, interchangeable plug-and-play elements. See Figure 3 illustrating the framework guiding the design of the OR prototype, which is then depicted as a floor plan in Figure 4.

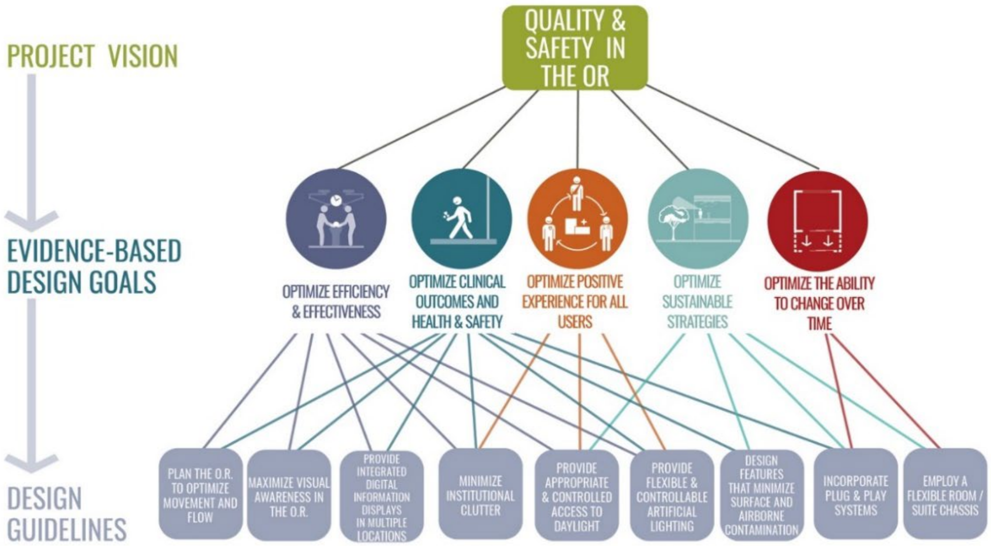


Figure 3: Diagram of framework guiding the design of the OR prototype.

OR Size and Shape

The overall net dimension of the final OR prototype was 22' x 26' or approximately 6.7 x 7.9 meters. With an alcove for parking a mobile circulating nurse workstation and storage, the net area of the room ended up being 579 square feet or 53.8 square meters. As described earlier, the area and dimensions were evaluated in simulation models through a comparison with larger and smaller room areas and dimensions. Findings from simulations (both mock-up based and computer based) indicated that the prototype room size and dimensions performed well for ambulatory pediatric and orthopedic procedures in terms of flow patterns and disruptions, showing fewer incursions into the sterile zone than smaller rooms and fewer travels/ steps than larger rooms (Taaffe et al., 2020).

OR Layout

The OR prototype fundamentally is organized into four designated zones around the sterile field at the OR table: an anesthesia work zone (AZ) at the head of the table, surgical work zones (SZ) on either side (depending on left- or right-side surgeries), and a circulating zone (CZ) at the foot and entry corner of the room. These zones were demarcated in the prototype by flooring colors, which facilitated the surgical flow according to focus groups. The surgical table placement and orientation off center and diagonal in the room opens up the foot and side areas around the table for circulation, equipment, and procedure setup. The surgical table placement also positions the anesthesia work area in a more protected location, less prone to intrusion of other surgical team members. Our observational studies of workflow and movement in the OR found that anesthesia providers experienced the highest rates of disruptions (Joseph et al., 2019; Jurewicz et al., 2018) and that workspace design challenges exacerbated the impacts of the observed high rates of task switching among this group of clinicians (Jurewicz et al., 2019; Jurewicz et al., 2021).

According to simulations and the POE, the atypical positioning of the surgical table also allows for more efficient and effective use of space in the room by eliminating the need to access space typically found in the far corner of the room, behind the anesthesia boom and between the primary surgical zone and anesthesia zones, which otherwise would be accessed by passing through either the anesthesia or surgeon workstation zones. Furthermore, research findings showed that the surgical table orientation and placement away from the patient entry door facilitates maneuvering and minimizes effort during patient bed flow in and out of the room.

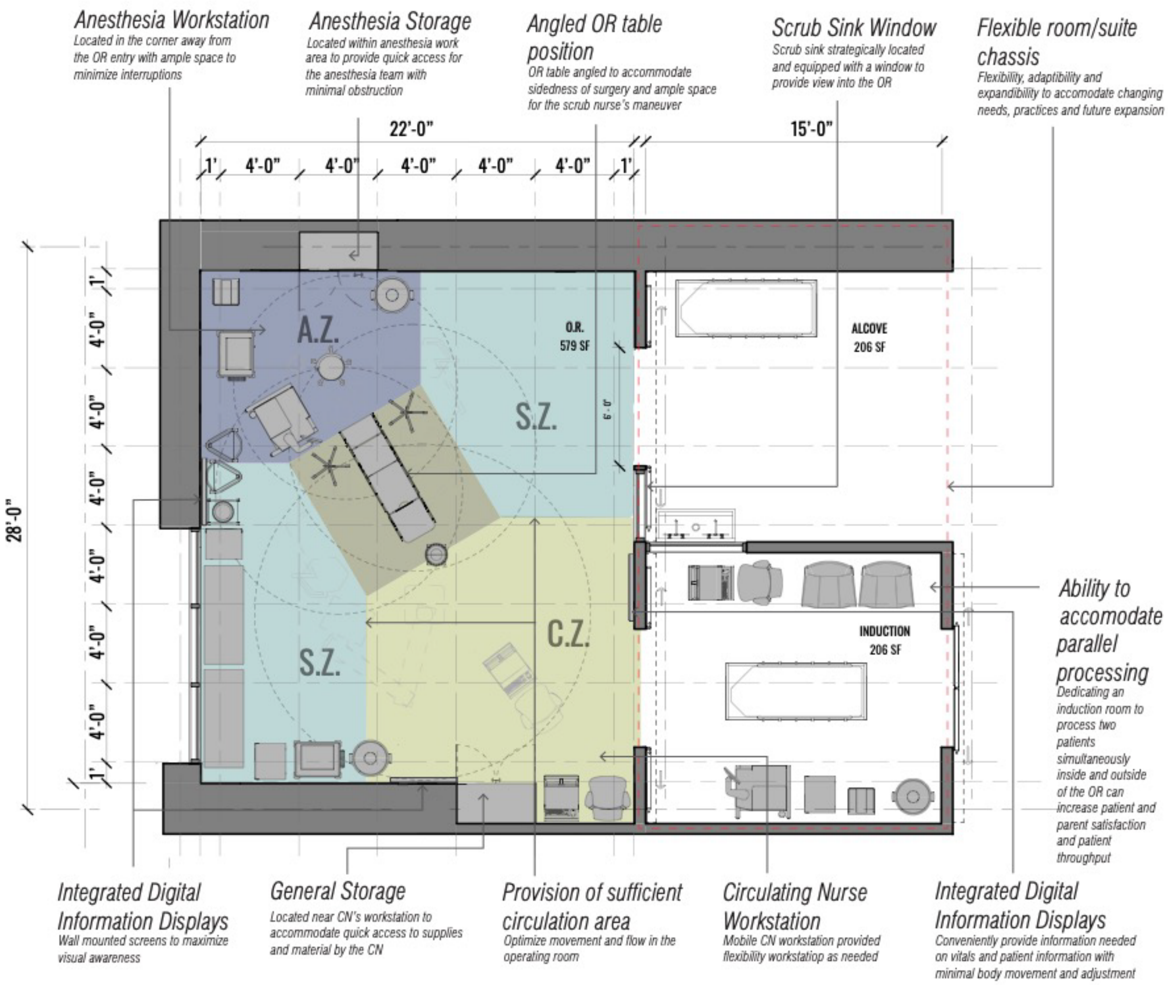


Figure 4: Annotated floor plan of the final OR prototype.

Mobile Circulating Nurse Workstation

The analysis of surgery video data found that the circulating nurse makes frequent trips to the surgical table and to storage areas to support the team. Further, many disruptions occur at the foot of the table, often involving the circulating nurse (Bayramzadeh, Joseph, San, et al., 2018; Neyens et al., 2018). Another study found that areas of high traffic in the OR were correlated with higher microbial load (Taaffe et al., 2018), indicating the need to reduce unnecessary travel inside the OR. Based on feedback from mock-up--based simulations and video observations, the OR prototype proposed a mobile circulating nurse workstation that allows flexibility in the positioning of the nurse during surgery, allowing repositioning based on visibility and flow needs. The mobile workstation minimizes the need to move around constantly during the surgery. This enables the circulating nurse to optimally position the workstation to view the procedure while documenting or monitoring the surgery in the computer. A parking alcove is provided for this workstation when it is not in use (e.g., during turnaround or postoperative phases). Observations and focus groups also highlighted the importance of cord management, outlet positioning, and the location of environmental control devices (e.g., lighting) with regard to the mobile workstation, because the unit requires a power outlet for charging, and some staff reported a preference for having the workstation plugged in at all times.

Information Displays

The OR prototype was designed with integrated patient information retrieval and display technology in addition to adjustable boom-mounted displays around the surgical table. Proposed wall-mounted information displays were located on three walls of the prototype, envisioning a continuous band of digital display integrated into the wall panels surrounding the entire room. The prototype was fabricated with three wall-mounted monitors, one on each long wall and one on the foot wall of the room. Aiming to enhance situational awareness, displays were positioned to allow optimal visibility for the entire surgical team at any time during the surgery, on either side of the surgical table, and while moving around the room. Simulations found that displays were initially installed too high for comfortable viewing and that sight lines were blocked from some points by overhead surgical booms and lights (Joseph et al., 2021).

OR Flexibility

Based on observations at one of the case studies visited and simulations conducted during the design process, the prototype chassis was designed to accommodate the option of an adjoining induction room for pediatric cases. Given that most pediatric surgeries are of a short duration with a longer preoperative stage involving induction, a separate room allows the next case to begin the induction process with a separate anesthesia team outside of the OR while a procedure is in progress. This enables parallel processing, with quicker turnaround times and throughput of surgical cases each day. The separate induction room also allows family members to be with the child during the intimidating induction process without the need for gowning.

Simulations showed that the configuration of the OR prototype was able to accommodate these different configurations with minor changes, incorporating adjoining ancillary rooms, such as an induction room or postoperative instrument breakdown room and a scrub sink/entry alcove. The prototype was tested in simulation for both postoperative instrument breakdown associated with orthopedic surgeries and induction outside the OR for pediatric surgery. The induction room scenarios were viewed as beneficial for short-duration pediatric cases and ultimately were adopted in the subsequently built facility as a means to improve room turnover and overall productivity (Joseph et al., 2021).

The prototype was built with a modular and adaptable overhead structural frame to support surgical booms, surgical lights, and other ceiling-mounted items. It was designed to enable the relocation of these overhead elements with minimal effort and cost. The simulations did not explicitly evaluate the original placement of overhead surgical booms and lights, although anecdotal feedback indicated that there was some difficulty in optimally positioning the surgical boom and lights across different procedures and clinician positioning. Insights indicated that the mounting locations of the booms were too close to the center of the OR table and would be better placed further apart to minimize conflicts in boom rotations.

Safe OR Design Tool

The interactive web-based Safe OR Design tool provides an opportunity to interact with components in an OR environment through a 3D model. The web interface also allows users to explore design strategies and their associated desired outcomes for a series of design elements commonly found in OR environments. Additionally, users of the tool may filter design strategies by the type of strategy it is within the work system and access citations associated with each design strategy. The Safe OR Design Tool (http://ordesign.clemson.edu/or_design_toolkit) contains the following components:

1. **Design Elements:** A series of 14 design elements provide a focused platform for accessing design strategies and desired outcomes for commonly found features within the OR environment.
2. **Design Strategies:** These actionable statements provide guidance on how to implement a design strategy into the OR environment to support a desired outcome.
3. **Rationale:** An associated description is provided for each design strategy, addressing why that specific strategy is important to consider based on current literature or PSLL findings.
4. **Desired Outcomes**: Desired outcomes that have been linked with evidence to the associated design strategy are provided to address how the design strategy can improve safety and quality in the OR.
5. **Type of Evidence:** The type of evidence, broken into four distinct categories, and full citation for each combination of design strategy and desired outcome are provided for users' reference.
6. **Type of Strategy:** Each design strategy is tagged to provide insight into which OR work system component is impacted by the associated design strategy. The following five types of strategies are included in this tool: People, Task, Organization, Technology, and the Built Environment.

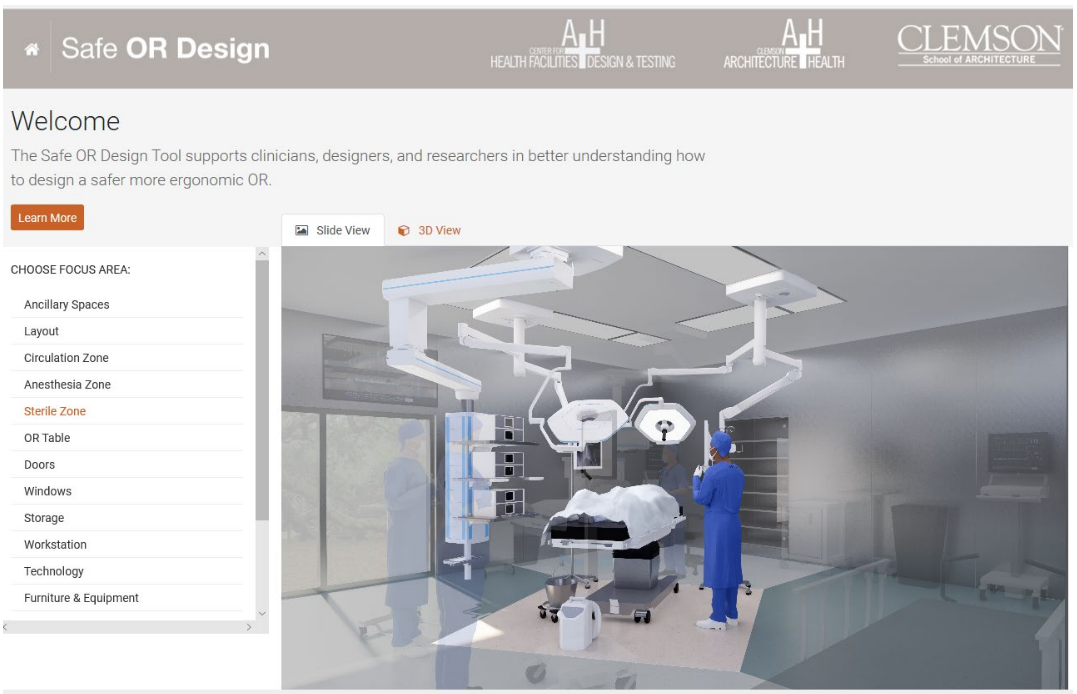


Figure 5: Safe OR design tool web interface.

Implementation of OR Prototype in the R. Keith Summey Pediatric Ambulatory Surgery Center

Largely designed to reflect findings from the simulations, the ORs built in the Ambulatory Surgery Center (ASC) were similar to the OR prototype in overall size and layout (e.g., location/position of the surgical table) and different in terms of features, such as the number and position of doors and information displays.

See Figure 6, comparing the OR prototype with the OR that was implemented at the ASC.

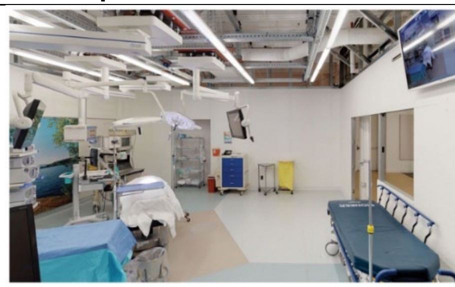
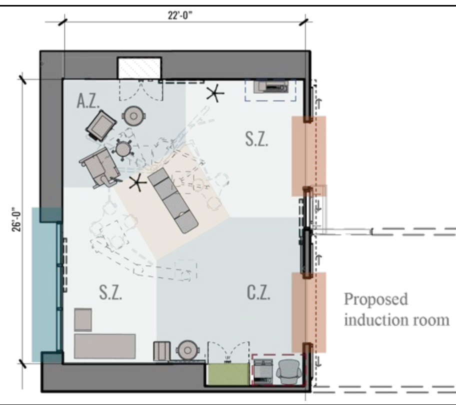
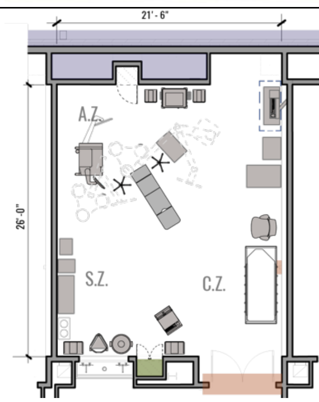
	Mock-up OR	**Built OR**
Room photo		
Room plan		
OR size	22' x 26' / 579 square feet / 53.8 square meters	22' x 26' / 579 square feet / 53.8 square meters
Induction room location	Physically adjacent to OR	Located across the corridor from the OR
Door location	On longer OR wall	On shorter OR wall
Door type	Sliding door	Swing door
Visual displays	Two ceiling-mounted monitors Three large wall-mounted displays	Two ceiling-mounted monitors No large wall-mounted displays
Flooring pattern	Rooms zones clearly demarcated by pattern	No pattern (uniform flooring)
Window	Simulated window views and access to daylight	No window views or access to daylight
Scrub sink location	Adjacent to OR, along longer wall With direct window view into OR	Adjacent to OR, along shorter wall With direct window view into OR
Circulating nurse Workstation	Alcove for workstation 'parking'	No alcove for workstation 'parking'
Surgeon Workstation	Positioned at short wall, close to anesthesia area	Positioned at long wall, close to anesthesia area

Figure 6: Comparison between OR prototype and built ASC OR.

Figure 7: ORs in the MUSC pediatric ambulatory surgery center, featuring integrated design concepts generated over several years of the PSLL.

Post-occupancy Evaluation

The size, dimensions, and configuration of the OR prototype enabled an effective and efficient use of its space. As a major finding validated by simulations as well as the POE, placing the surgical table diagonally and off center in the rectangular shaped room, away from the entry door, improved movement and flow in the OR, facilitating patient entry, transfer, and positioning. Additionally, this position of the surgical table facilitates movement around the room without interfering with the anesthesia and sterile zones around the patient, avoiding flow disruptions in these areas, such as bumps, trips, and related safety risks for patients and staff (Joseph et al., 2021). The prototype design, with the location and orientation of the surgical table, the mobile nurse workstation, and multiple wall-mounted information displays, was also successful in improving situational awareness. Combined, these features enabled ample visibility between surgical team members and facilitated movement for the circulating nurse, a critical role supporting the entire surgical procedure. As charging capacity and reliability improve, control devices become more available on wireless devices and smart system integration becomes more widely adopted, thus increasing the flexibility and capacity to position and operate mobile workstations in the OR. Simulations of the prototype mock-up indicated that the overall room design provides flexibility for a variety of pediatric and orthopedic ambulatory procedures requiring different surgical teams, equipment, and positioning of the procedure and team members.

Limitations

Most of the limitations on evaluating the prototype design were known at the outset and framed by the scope of the study, schedule, budget, and mock-up site. The prototype evaluations were focused on a limited set number of ambulatory pediatric and orthopedic surgical procedures. Several architectural design features of the OR prototype were not evaluated due to a variety of limitations. The research did not study issues of overall room lighting or evaluate the configuration of overhead booms and surgical lights. Due to the nature of simulations and overall constraints of space, time, and funding, the prototype did not include mechanical systems, nor could actual surgical procedures be performed (for obvious reasons), so the study did not evaluate the mock-up design in terms of infection control. Based on similar limitations, the study did not evaluate the impact of artificial lighting scenes, daylight, or connections to nature for either patients or staff, even though considerable attention went into considering these attributes in the prototype design. Likewise, the study could not test issues of flexibility beyond accommodating the select range of pediatric ambulatory surgery procedures. These issues all deserve further consideration and evaluation in the future.

Conclusions and Significance

The work products and research publications developed as part of the RIPCHD.OR PSLL represent the most comprehensive body of work related to operating room work systems design. In addition to the traditional peer-reviewed publications and conference presentations, the range of other innovative products includes well-illustrated online books, a web-based tool, physical prototypes, and the *'Innovations in Surgical Environments Workshop.'* These different modes allowed this work to be disseminated quickly and effectively and have already made a significant impact on the industry. The design, process, and technology solutions that emerged from this learning lab were implemented at the new MUSC Ambulatory Surgery Center in South Carolina and at the Emory Executive Park Musculoskeletal Institute in Georgia. Plans are underway to conduct a similar POE at the Emory facility in 2022. The lessons learned from this project have also influenced the design of several surgery center projects around the US and will provide the foundation for future research related to other types of OR environments, such as hybrid ORs and robotic-assisted surgeries. The research and prototype design framework and methods that were developed, employed, and refined through this project are envisioned to be applicable to other healthcare spaces where critical patient care and treatment are delivered and in settings that are replicated over-and-over again in the design of healthcare facilities. Work from this research project has been extended into another AHRQ grant-funded research study focused on reducing errors in perioperative anesthesia medication delivery. This new research project is a collaboration between the Medical University of South Carolina, Clemson University, and Johns Hopkins University and will continue through 2022. This project has also made a significant impact on all faculty and students involved with the project, resulting in a transdisciplinary team that now has the capability to tackle similar complex problems to make healthcare environments safer.

6. List of Publications and Products

Publications

1) Joseph A, Mihandoust S, Wingler D, Machry H, Allison D, Reeves S. Comparing user perceptions of surgical environments: Simulations in a high-fidelity physical mock-up versus a postoccupancy evaluation. *Health Environments Research & Design Journal*. 2021 September 13; doi: 10.1177/19375867211044733 https://doi.org/10.1177/19375867211044733
2) Joseph A, Neyens D, Mihandoust S, Taaffe K, Allison D, Prabhu V, Reeves S. Impact of surgical table orientation on flow disruptions and movement patterns during pediatric outpatient surgeries. I*nternational Journal of Environmental Research and Public Health*. 2021 July 31; 18:8114. doi: 10.3390/ijerph18158114 https://doi.org/10.3390/ijerph18158114
3) Joseph A, Reid J, Kearney J. Planning Patient Care Areas Using Simulation. In E.S. Deutsch, S.J. Perry, & H.G. Gurnaney (Eds.), *Comprehensive Healthcare Simulation: Improving Healthcare Systems* (pp. 97-105). Cham: Springer International Publishing, July 2021;97-105, ISBN: 978-3-030-72973-8; doi: 10.1007/978-3-030-72973-8_14

4) Allison D, Machry H, Joseph A. Design insights from a research initiative on ambulatory surgery operating rooms in the U.S. *Instituto de Pesquisas Hospitalares (IPH) Magazine.* 2021 May; 17:212-229, ISSN 2358-3630.
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6) Machry H, Joseph A, Wingler D. The fit between spatial configuration and idealized flows: Mapping flows in surgical facilities as part of case study visits. *Health Environments Research & Design Journal.* 2020 May 29; doi: 10.1177/1937586720928350 https://doi.org/10.1177/1937586720928350
7) Taaffe K, Joseph A, Khoshkenar A, Machry H, Allison D, Reeves ST; RIPCHD.OR Study Group. Proactive evaluation of an operating room prototype: A simulation-based modeling approach. *Journal of Patient Safety.* 2020 March 13; doi: 10.1097/PTS.0000000000000693 PMID: 32175960 https://doi.org/10.1097/PTS.0000000000000693
8) Joseph A, Khoshkenar A, Taaffe KM, Catchpole K, Machry H, Bayramzadeh S; RIPCHD.OR study group. Minor flow disruptions, traffic-related factors and their effect on major flow disruptions in the operating room. *BMJ Qual Saf.* 2019 April; 28(4):276-283. doi: 10.1136/bmjqs-2018-007957 http://dx.doi.org/10.1136/bmjqs-2018-007957
9) Jurewicz KA, Neyens DM, Catchpole K, Reeves ST. Developing a 3D gestural interface for anesthesia-related human-computer interaction tasks using both experts and novices. *Human Factors.* 2018 November; 60(7): 992-1007. https://doi.org/10.1177%2F0018720818780544
10) Mousavi E, Jafarifiroozabadi R, Bayramzadeh S, Joseph A, San D. An observational study of door motion in operating rooms. *Building and Environment.* 2018 October 15; 144: 502-507. https://doi.org/10.1016/j.buildenv.2018.08.052
11) Wingler D, Machry H, Bayramzadeh S, Joseph A, Allison D. Comparing the effectiveness of four different design media in communicating desired performance outcomes with clinical end users. *Health Environments Research & Design Journal.* 2018 August 30; doi: 10.1177/1937586718796626 https://doi.org/10.1177/1937586718796626
12) Joseph A, Khoshkenar A, Taaffe K, Catchpole K, Machry H, Bayramzadeh S. Minor flow disruptions, traffic-related factors and their effect on major flow disruptions in the operating room. *BMJ Quality & Safety.* 2018 August 29; 0:1-8. doi: 10.1136/ bmjqs-2018-007957 http://dx.doi.org/10.1136/bmjqs-2018-007957
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15) Neyens DM, Bayramzadeh S, Catchpole K, Joseph A, Taaffe K, Jurewicz K, Khoshkenar A, San D; RIPCHD.OR Study Group. Using a systems approach to evaluate a circulating nurse's work patterns and workflow disruptions. *Applied Ergonomics.* 2018 March 30; https://doi.org/10.1016/j.apergo.2018.03.017 PMID: 29609835

16) Bayramzadeh S, Joseph A, San D, Khoshkenar A, Taaffe K, Jafarifiroozabadi R, Neyens D; RIPCHD.OR Study Group. The impact of operating room layout on circulating nurse's work patterns and workflow disruptions: A behavioral mapping study. *Health Environments Research & Design Journal.* 2018 January; https://doi.org/10.1177%2F1937586717751124 PMID: 29355033
17) Jurewicz K, Alfred M, Neyens D, Catchpole K, Joseph A, Reeves S. Investigating Intraoperative and Intraprofessional Handoffs in Anesthesia. Proceedings of the 62nd Annual Meeting of the Human Factors and Ergonomics Society. 2018; Philadelphia, PA.
18) Joseph A, Bayramzadeh S, Zamani Z, Rostenberg B. Safety, performance, and satisfaction outcomes in the operating room: A literature review. *Health Environments Research & Design Journal.* 2018 April; 11(2):137-150. https://doi.org/10.1177%2F1937586717705107 PMID: 28436232
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20) Khoshkenar A, Taaffe K, Muhs M, Fredendall L, Ferrand Y, Joseph A, San D. Simulation-based design and traffic flow improvements in the operating room. Proceedings of 2017 Winter Simulation Conference (WSC). 2017.
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22) Betza SM, Jurewicz KA, Neyens DM, Riggs S, Abernathy JH, Reeves S. Anesthesia maintenance and vigilance examining task switching. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.* 2016; 60(1):608-612. https://doi.org/10.1177%2F1541931213601139

Other Products:

Safe OR Design Tool
http://ordesign.clemson.edu/or_design_toolkit

RIPCHD.OR volumes 1,2, and 3
https://issuu.com/clemsonchfdt

Videos of simulation-based evaluations
https://www.youtube.com/channel/UCymoJ1H9iJ1I4JxgzoL92ug

RIPCHD.OR 3D Views
The 3D view shows the high-fidelity mock-up that was constructed at the Clemson Design Center at Charleston. Some of the key features are modular wall systems, optimal room size and angled position of the bed, work zones clearly demarcated with flooring and spatial layout, storage located in proximity to key work zones, and digital integration and increased visual awareness (through wall-mounted screens, sliding doors, and window views). Several surgical procedures were simulated over multiple rounds of testing and evaluations in this high-fidelity mock-up. To view the RIPCHD.OR prototype in 3D, please visit the following link:
https://my.matterport.com/show/?m=RZPzh1SgKxV&fbclid=IwAR0svro5Mtyaj_BAm7Qo2RHidPKztzzHVoEKIRm6iqBIr5OitoSWgRLq4eg

Surgical Environments Workshop

In 2019, the RIPCHD.OR team held an ambulatory surgery center design workshop at the Clemson Design Center in Charleston (CDCC). The 2-day, intensive event explored how different aspects of surgery center design impact patient safety, efficiency, and patient experience and provided attendees with actionable tools and approaches to support project teams in the design process. The Innovations in Surgical Environments workshop represented a culmination of the 4-year, multidisciplinary RIPCHD.OR research effort on different aspects of ambulatory surgery center design. The event involved around 100 attendees, including advisory committee members, industry experts, designers, clinicians, and healthcare administrators. The goal of the event was to provide industry leaders with in-depth knowledge of surgical center design and support others in applying a human-centered approach to their current or future OR projects.