Realizing Improved Patient Care through Human-centered Operating Room Design

A Human Factors Methodology for Observing Flow Disruptions in the Cardiothoracic Operating Room


ABSTRACT

Background: Human factors engineering has allowed a systematic approach to the evaluation of adverse events in a multitude of high-stake industries. This study sought to develop an initial methodology for identifying and classifying flow disruptions in the cardiac operating room (OR).

Methods: Two industrial engineers with expertise in human factors workflow disruptions observed 10 cardiac operations from the moment the patient entered the OR to the time they left for the intensive care unit. Each disruption was fully documented on an architectural layout of the OR suite and time-stamped during each phase of surgery (preoperative [before incision], operative [incision to skin closure], and postoperative [skin closure until the patient leaves the OR]) to synchronize flow disruptions between the two observers. These disruptions were then categorized.

Results: The two observers made a total of 1,158 observations. After the elimination of duplicate observations, a total of 1,080 observations remained to be analyzed. These disruptions were then categorized.

Conclusions: By using the detailed architectural diagrams, the authors were able to clearly demonstrate for the first time the unique role that OR design and equipment layout has on the generation of physical layout flow disruptions. Most importantly, the authors have developed a robust taxonomy to describe the flow disruptions encountered in a cardiac OR, which can be used for future research and patient safety improvements.

What We Already Know about This Topic

- Operating room configuration has developed haphazardly and differs among institutions.
- The investigators used human factors analysis to identify and classify flow disturbances (any factor impeding work or communication) during cardiac surgery.

What This Article Tells Us That Is New

- There were an average of approximately 100 flow disturbances per case.
- One third of the disturbances were related to operating room layout and design.

MORBIDITY and mortality reductions in surgery have mostly been made through improvements in anesthesia, surgical techniques, antibiotics, and intensive care medicine. As technological advances in equipment and procedures occurred, the operating room (OR) has become an extremely complex environment. This growing
technologically rich environment has led to new challenges in patient safety. Human factors engineering has allowed a systematic approach to the evaluation of adverse events in a multitude of high-stake industries including aviation, mining, and nuclear power.1–4 The development of simple tools, such as checklists and simulation training scenarios, has cumulated in a substantial decrease in measurable adverse outcomes including injuries and deaths in these industries.9

Despite great work by groups such as the Flawless Operative Cardiovascular Unified Systems project sponsored by the Society of Cardiovascular Anesthesiologists,10 the progression of human factors engineering into health care has been arduous. Starting from 1950s, anesthesiologists began to investigate the incidence of adverse events and 20 yr later began to apply human factors engineering and system approach techniques in an early attempt to improve patient safety.7,8,11–17 Unfortunately, the sentinel event reporting approach techniques in an early attempt to improve patient safety.‡‡ Unfortunately, the sentinel event reporting process continues to be the predominant mechanism used to identify systemic factors affecting patient safety.‡‡ This process has far too often focused exclusively on the “performance” of the surgeon or other members of the intraoperative team and has not offered the descriptive details necessary to identify environmental factors that may have affected performance.16,18–21

The OR contains multiple personnel (anesthesiologists, surgeons, nurses, and perfusionists), numerous different materials, a multitude of tools, and various equipment making it an incredibly complex system. The aviation industry has succeeded in improving safety and reducing system errors by identifying the cause of air crashes through the establishment of the Human Factors Analysis and Classification System.4–6 Although much work has been done, medicine remains behind aviation in the identification of these errors.

Wiegmann, Gawande, Christian, Martinez, and others have performed observational studies in a variety of surgical procedures to identify adverse events and common threads.23,24 Elbardi interviewed staff at Mayo Clinic ORs and categorized staff’s perceived errors into four categories such as organizational influences, unsafe supervision, preconditions for unsafe acts, and unsafe acts. Christian and Martinez both used direct observational analysis of OR systems to identify latent and active conditions that could predispose the system to error. Human factors engineers describe disruptions in flow as a preceding event in the majority of errors in the OR. Whether as seemingly trivial as tripping over a cord on the floor or spilling saline to much more disrupting events such as not having the needed equipment for a valve replacement, these “flow disruptions” introduce unwanted distractions and open the door for errors to occur.


The manner in which flow disruptions are recorded and the nomenclature/classification system for documenting them has varied significantly from study-to-study making direct comparisons and generalizations difficult. This study sought to develop a framework/methodology for identifying and classifying flow disruptions in the cardiac OR. In doing so, this study will provide the foundation for a standardized flow disruption taxonomy among those investigating precursor events in the OR.

Materials and Methods

Facility Description

The Medical University of South Carolina is a large metropolitan healthcare complex with more than 700 hospital beds, multiple ORs, and a long-established medical school. A variety of cardiac surgical procedures are performed within two state-of-the-art surgical suites built as part of a new replacement facility in 2008. An architectural floor plan and layout of the typical cardiac surgical suite at Medical University of South Carolina are illustrated in figure 1. The anesthesia area is located at the head of the operating table (top-center of image), which includes a general anesthesia machine complete with multiple stacked monitors to the left and a transesophageal echocardiography machine to the right. The perfusion area is located to the right of the operating table and includes a standard cardiopulmonary bypass machine and small ancillary tables. To the left of the operating table are a series of tables for surgical instruments and surgical supplies managed by the surgical and circulating nurse. The area at the foot of the surgical table is relatively unencumbered and provides space for observation and a passage to the OR exit (lower right) and access to the surgical core for the circulating nurse (lower left). Three overhead booms are also shown in dashed lines and include ones for anesthesia, surgical, and perfusion equipments.

Observers

A team of collaborators from Clemson University consisting of industrial engineers and healthcare architects with expertise in human factor methodology along with cardiothoracic anesthesiologists from the Medical University of South Carolina combined to form the Realizing Improved Patient Care through Human-centered OR Design (RIPCHORD) study group. From the RIPCHORD study group, two industrial engineers with graduate level training in human factors engineering were tasked with observing workflow within the cardiac surgical suite from the moment the patient was brought into the OR to the time they were transported to the intensive care unit. Unlike previous studies,22,23,25,26 our objective was not to explore specific medical errors; rather, to document potential threats to patient safety as a result of workflow disruptions—specifically, those associated with human factors. Before the study, the observers
were familiarized with cardiac surgical procedures and ORs. Although the observer's familiarity with the surgical procedure was beneficial, their expertise in human factors was critical to the task. The observations were conducted solely by well-trained human factors experts rather than healthcare professionals with limited formal training in human factors. Unique to this study was the use of specific architectural graphic layouts of the OR and equipment at each phase of surgery (preoperative, operative, and postoperative), which were developed by the Clemson healthcare architects from separate observations before observations by the industrial engineers. These layout diagrams were incorporated into an observational worksheet used by the human factors observers (fig. 1).

Fig. 1. Operative phase architectural plan layout. Architectural plan layout of the observed cardiac operating room during the intraoperative stage of a procedure illustrating equipment positioning, staff, and observers. (A) Region A is the anesthesia area and up to three anesthesiologists (faculty, fellow, and resident) occupy this location. Region B is the surgeon area with the attending surgeon, surgical fellow, medical student, and scrub nurse occupying this region. The circulating nurses mainly inhabit region C. Finally, region D is the perfusion area. (B) Photo of operative phase of cardiothoracic surgery. CPB = cardiopulmonary bypass; IV = intravenous; TEE = transesophageal echocardiography.
**Observations**

After the approval by Medical University of South Carolina (Charleston, South Carolina) and Clemson University (Clemson, South Carolina) institutional review board, 10 cardiac surgeries were observed over a 2-week period including aortic valve replacement, mitral valve replacement, and coronary artery bypass grafting surgeries. As an institutional review board exempt study, informed consent was not necessary to obtain. Every procedure had similar personnel, staff interaction, and room set-up. Anticipating at least 100 interruptions per case, 10 cases were required to reach 1,000 observations—enough to accurately develop a robust taxonomy of flow disruptions.

The objective of the study was to capture flow disruptions as they occurred during the observation period. Everyone who entered the surgical arena during the procedure was included in the observation analysis, including anesthesiologists, surgeons, nurses, and perfusionists. Figure 1A shows the placement of the two observers in the OR. Neither observer was within the sterile field nor did they interfere with healthcare staff activities. Observations began during room set-up, continued after the patient was transported to the intensive care unit and included room cleanup. Three phases of the operation were defined as preoperative: time from patient in room to incision; operative: time from incision to completion of the operation; and postoperative: time from the completion of the operation to when the patient left the OR for the intensive care unit.

Observers were instructed to identify any disruption to the normal flow of operations. This could include equipment and/or communication failures, physical obstructions, distractions, and even usability issues (e.g., spills, software trouble, trips). Observer 1 was responsible for the anesthesia, perfusion, and surgical areas, whereas observer 2 was responsible for the nursing and surgical areas.

Each disruption was fully documented on an architectural layout of the OR suite and time-stamped using the clock in the OR to synchronize flow disruptions between the two observers. Information documented, included but was not limited to, who was involved, what happened, time it occurred, and where it occurred. The detailed layout of the room and equipment on the observation worksheet made it possible to not only document what happened, who was involved, and when it occurred, but also the specific location of the disruption. When both observers documented the same disruption, the single disruption was counted only once.

**Statistical Analysis**

Observations were organized and counted using Excel (Seattle, WA). Excel was used to calculate sums and proportions.

**Results**

**Development of Taxonomy**

The two observers made a total of 1,158 observations. Because there was some overlap of the observers’ responsibilities, the two sets of observations were screened for duplication. After elimination of duplicate observations, a total of 1,080 observations remained to be analyzed.

Three of the authors (two human factors doctoral students and a senior human factors professor with experience designing a prominent human factors taxonomy) reviewed the observational data from the first surgery for naturally occurring human factors clusters. Deductive, qualitative coding was applied, where each observation was organized into clusters or similar groupings before a meaning was associated to the information. This larger, more aggregate analysis yielded six distinct clusters (communication, usability, physical layout, environmental hazards, general interruptions, and equipment failures). The six clusters were then further differentiated into 33 subgroups using affinity clustering.

After the original taxonomic structure was developed with data from one surgery, the subgroups were validated and refined using the remaining nine surgeries into the final taxonomic structure depicted in table 1.

Each category provides its own range of subcategories to provide the best coverage of detail. Communication disruptions involve ineffective conversation within the OR and also mechanisms that prevented successful communication. Usability issues (e.g., mishandling of objects) resulted in a step within the surgical process from being efficiently achieved. Physical layout concerns were recorded when the surgical team was hindered from their task because of the design and objects in the environment. Environmental hazards included occurrences such as slipping or falling. Equipment failures tally specific personnel’s equipment during the procedure. Finally, general interruptions included extraneous issues, which normally occur but could be minimized to increase concentration.

**Flow Disruptions: Overall**

The data revealed wide variability between flow disruption categories. Flow disruptions associated with physical layout (31%) were most prevalent. General interruptions (24%), usability concerns (20%), and communication issues (15%) were also frequently observed. In contrast, environmental hazards and equipment failures were relatively rare occurring 9 and 1%, respectively (table 2 and fig. 2).

Among the more prevalent unique flow disruptions within the main categories were those associated with physical layout such as inadequate use of space (158) and wrongful positioning of furniture (81) and equipment (65). In the other main categories, spilling and dropping of items (117) and shift changes (70) were the most commonly observed interruptions during the 10 surgical procedures. Slips and/or falls and exposure to sharps were observed 62 and 6 times, respectively.

Usability was also a concern, but less specific as a variety of noncomputer equipment usability, such as television monitors, IV poles, beds, cameras, and lights, (91) were documented. Computer usability (i.e., software and data input

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Table 1. Description of Areas of Interest and Disruptions for Observational Taxonomy

Communication (verbal and nonverbal)
- Poor communication—communication between two or more individuals, which do not achieve its desired goal and is not captured by other categories within this area of interest.
- Lack of response—the failure of an individual to answer communication requiring a reply or confirmation.
- Confusion—a demonstrated lack of understanding associated with communication directed at the individual or otherwise intended for the use.
- Simultaneous communication—two or more individuals are communicating at the same time resulting in miscommunication or repetition of information.
- Nonessential communication—there are periods of time within any undertaking where attention must be focused on the task at hand and all nonessential communication (e.g., sports-talk, jokes, personal inquiries) must be eliminated.
- Environmental noise—the increasing sound level in the operating room may cause flow disruptions of communication, or decrease concentration of the current task.

Usability
- Computer—this category includes problems associated with operating software, programs, and utilities; however, usability issues associated with pointing devices, monitors, and other hardware are also included here.
- Equipment—usability and design issues associated with equipment other than computers and software-related devices such as iPads and smartphones.
- Surfaces—textures, colors, and other design-controlled attributes that inhibit optimal use.
- Barriers—there are numerous barriers erected for maintaining sterile fields. Problems associated with erecting those barriers or donning protective equipment (e.g., gloves, gowns, etc.).
- Packaging—issues associated with unwrapping, untying, or opening packaging containing supplies and instruments.
- Data entry (noncomputer)—this category includes usability issues associated with hard-copy data entry devices (e.g., forms, checklists, etc.).

Layout
- Connector positioning—the entanglement or misplacement of wires and tubes, which can hinder movement and continuation of a task.
- Equipment positioning—machines and tools may restrict or prevent the movement and actions of the staff.
- Furniture positioning—chairs, operating room bed, and desk can cause operating room staff to deviate from their original movement.
- Permanent structures positioning—doorways are frequently used in the operating room during surgical procedures, which prevent continuous movement and possible injury.
- Inadequate use of space—surface and floor space is used inappropriately through clutter, untidiness, congestion, and blockage.
- Impeded visibility—the staff may have objects, which obstruct their ability to see at important junctions during the procedure.

Environmental hazards
- Slipping/falling—operating room staff have the potential of slipping on liquids and materials on the floor while not being cognizant of surroundings.
- Sharps—incidents which involve the interaction of operating room staff with contaminated needles.
- Crushing—objects that are forced and wedged between unintentional spaces.

Interruptions
- Phone calls—incoming or outgoing calls occur which draw attention away from the surgical procedure.
- Pages—during surgery, pagers are given to the circulating nurse and interrupt the surgeons and anesthesiologists when each page comes in.
- Nonessential personnel—staff who are not essential to the cardiothoracic procedure are labeled as a distraction.
- Spilling/dropping items—when materials are dropped or spilled on the floor, the staff member is potentially diverted away from their current task.
- Teaching moments—moments when staff pause and teach students or trainees during the procedure.
- Outside distractions—disruptions external to the operating room that interfere with normal activities (e.g., noises in the passageway, fire alarms, etc.).
- Shift changes—during a shift changes among personnel, staff communicate about important details of the procedure and/or patient which might lead to others’ distraction.
- Searching activity—miscellaneous items become missing in the operating room and are pursued when they are needed immediately.
- Common information—information which every staff member should be knowledgeable of yet forgets and interrupts others to retrieve the information.

Equipment failure
- Surgeons equipment—equipment which malfunctions during surgery used by surgeons.
- Anesthesia equipment—equipment which malfunctions during surgery used by anesthesiologists.
- Perfusion equipment—equipment which malfunctions during surgery used by perfusionists.
devices) were also identified, but at a rather low frequency (26). Physical layout concerns dealing with entanglement and handling difficulty of tubes and wires (connector positioning) also accounted for 19 flow disruptions.

A variety of communication issues were noted as well. For example, poor communication between the OR staff, including anesthesiologists, surgeons, nurses, and perfusionists, were observed 72 times over the course of the study. There were also times when confusing information was relayed (33) and had to be clarified or repeated. On 25 separate occasions, a lack of response from OR staff led to a repeated query, thereby disrupting the normal flow of operations.

**Flow Disruptions during Specific Phases of the Operation**

Flow disruptions by phase of operation were of particular interest. An inspection of figure 2 reveals that the pattern of flow disruptions varied by phase of operation. Specific frequency and percentage data are presented in table 2. Each percentage is calculated within the specific category and phase of operation (vertically). During the preoperative phase when only a selected subset of OR staff are present, flow disruptions were dominated by physical layout issues (152), which were nearly double those related to usability (80) and general interruptions (76). Specifically, inadequate use of space (65) was the main concern with regard to

<table>
<thead>
<tr>
<th>Flow Disruption</th>
<th>Preoperative</th>
<th>Operative</th>
<th>Postoperative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor communication</td>
<td>10 (31%)</td>
<td>60 (50%)</td>
<td>2 (20%)</td>
</tr>
<tr>
<td>Lack of response</td>
<td>9 (28%)</td>
<td>16 (13%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Confusion</td>
<td>7 (22%)</td>
<td>21 (18%)</td>
<td>5 (50%)</td>
</tr>
<tr>
<td>Simultaneous communication</td>
<td>0 (0%)</td>
<td>5 (4%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Nonessential communication</td>
<td>2 (6%)</td>
<td>8 (7%)</td>
<td>2 (20%)</td>
</tr>
<tr>
<td>Environmental noise</td>
<td>4 (13%)</td>
<td>10 (8%)</td>
<td>1 (10%)</td>
</tr>
<tr>
<td>Usability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computer</td>
<td>9 (11%)</td>
<td>16 (15%)</td>
<td>1 (3%)</td>
</tr>
<tr>
<td>Equipment</td>
<td>31 (39%)</td>
<td>52 (50%)</td>
<td>8 (23%)</td>
</tr>
<tr>
<td>Surfaces</td>
<td>16 (20%)</td>
<td>24 (23%)</td>
<td>20 (57%)</td>
</tr>
<tr>
<td>Barriers</td>
<td>10 (13%)</td>
<td>0 (0%)</td>
<td>3 (9%)</td>
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<td>Packaging</td>
<td>9 (11%)</td>
<td>8 (8%)</td>
<td>2 (6%)</td>
</tr>
<tr>
<td>Data entry (noncomputer)</td>
<td>5 (6%)</td>
<td>5 (4%)</td>
<td>1 (3%)</td>
</tr>
<tr>
<td>Physical layout</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connector positioning</td>
<td>5 (3%)</td>
<td>8 (5%)</td>
<td>6 (15%)</td>
</tr>
<tr>
<td>Equipment positioning</td>
<td>28 (18%)</td>
<td>23 (16%)</td>
<td>14 (36%)</td>
</tr>
<tr>
<td>Furniture positioning</td>
<td>44 (29%)</td>
<td>27 (19%)</td>
<td>10 (26%)</td>
</tr>
<tr>
<td>Permanent structure positioning</td>
<td>7 (5%)</td>
<td>0 (0%)</td>
<td>1 (2%)</td>
</tr>
<tr>
<td>Inadequate use of space</td>
<td>65 (43%)</td>
<td>82 (57%)</td>
<td>11 (21%)</td>
</tr>
<tr>
<td>Impeded visibility</td>
<td>3 (2%)</td>
<td>5 (3%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Environmental hazards</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slipping/falling</td>
<td>24 (63%)</td>
<td>29 (78%)</td>
<td>9 (53%)</td>
</tr>
<tr>
<td>Sharps</td>
<td>2 (5%)</td>
<td>3 (8%)</td>
<td>1 (6%)</td>
</tr>
<tr>
<td>Crushing</td>
<td>12 (32%)</td>
<td>5 (14%)</td>
<td>7 (41%)</td>
</tr>
<tr>
<td>General interruptions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phone calls</td>
<td>3 (4%)</td>
<td>6 (4%)</td>
<td>1 (4%)</td>
</tr>
<tr>
<td>Pages</td>
<td>0 (0%)</td>
<td>10 (6%)</td>
<td>4 (17%)</td>
</tr>
<tr>
<td>Nonessential personnel</td>
<td>1 (1%)</td>
<td>5 (3%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Spilling/dropping items</td>
<td>41 (54%)</td>
<td>63 (41%)</td>
<td>13 (54%)</td>
</tr>
<tr>
<td>Teaching moments</td>
<td>3 (4%)</td>
<td>9 (6%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Outside distractions</td>
<td>3 (4%)</td>
<td>10 (6%)</td>
<td>2 (8%)</td>
</tr>
<tr>
<td>Shift changes</td>
<td>20 (26%)</td>
<td>46 (30%)</td>
<td>4 (17%)</td>
</tr>
<tr>
<td>Searching activities</td>
<td>5 (7%)</td>
<td>1 (1%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Common information</td>
<td>0 (0%)</td>
<td>4 (3%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Equipment failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surgeon equipment</td>
<td>2 (50%)</td>
<td>3 (42%)</td>
<td>2 (100%)</td>
</tr>
<tr>
<td>Anesthesia equipment</td>
<td>1 (25%)</td>
<td>2 (29%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Perfusion equipment</td>
<td>1 (25%)</td>
<td>2 (29%)</td>
<td>0 (0%)</td>
</tr>
</tbody>
</table>

Each percentage is calculated within the specific category and phase of operation (vertically).
physical layout incidents in the preoperative phase followed by incorrect positioning of furniture (44) and equipment (28).

During the operative phase, general interruptions (154) were slightly more prevalent than physical layout issues (145). The most frequent unique subcategories found in the operative phases were the inadequate use of space (82), spilling and dropping materials (63), and poor communication (60). However, unlike the preoperative period, considerably more communication and usability issues were documented. Comparing pre- and operative phases, general interruptions doubled and communication concerns nearly quadrupled.

The comparison of all three phases of the operation with respect to main and subcategories is illustrated in table 2. For the preoperative phase (65 [43%]) and the operative phase (82 [57%]), inadequate use of space was the most frequently observed layout issue. For the Postoperative phase, equipment positioning was the most frequently observed disruption (14 [36%]). Not surprising, issues associated with positioning of equipment and furniture were proportionally consistent across the preoperative and operative phases of surgery.

The disparity between preoperative and operative phases of surgery was less evident for the category of usability (preoperative: 80; operative: 105) with equipment use being the most prevalent operative flow disruption observed. A total of 120 communication issues were observed during the operative phase, whereas only 32 were observed during the preoperative phase, with poor communication being the most common operative communication-related disruption observed.

Fewer disruptions were observed for the postoperative phase, which was attributed to the diminished number of OR staff present, thereby reducing the overall opportunity for flow disruptions. Nevertheless, issues with the physical layout and usability of items were identified (table 3).

**Flow Disruption for Personnel Type**

Disruptions were categorized by personnel type (anesthesiologist, surgeon, nurse, and perfusionist) to determine whether a specific flow disruption cluster differentiated itself from the others. The causes of flow disruptions in each personnel type are shown in table 3 and figure 3.

**Anesthesiologists**

Amongst the anesthesiology team’s flow disruptions, physical layout issues (95) were the most prevalent followed by usability issues (69) and general interruptions (47). Of all personnel, anesthesiologists had the highest, although infrequent, occurrence of equipment failure (table 3).

**Surgeons**

Surgeons had the fewest number of flow disruptions out of all four personnel-type groupings. Their largest category of flow disruption occurred in communication (40). The surgeon’s most prevalent flow disruptions within the main category of communication are poor communication (20), nonresponsive communication (5), confusion (5), and environmental noise (5).

**Nurses**

Nursing flow disruptions are prominent in three categories such as general interruptions (119), usability (77), and communication (54). In the general interruption category, the leading issues are spilling/dropping materials, shift changes, and outside distractions.

**Perfusionists**

Similar to the anesthesiologists, the perfusionists’ leading cause of flow disruptions are physical layout issues (137), where the inadequate use of space (73), and wrongful positioning of equipment (29) and furniture (24) are the
prominent subcategory disruptions. Physical layout flow disruptions grouped under the perfusion area more than doubled the number from the other categories. The categories that follow physical layout issues are general interruptions (66) and usability concerns (61).

**Disruptions and Personnel Movement as They Related to OR Layout: A New Way to Investigate Errors**

Figure 4 represents composite movements of personnel (anesthesiologists, surgeons, nurses, and perfusionists) during the operative phase of observed cases. Unique personnel classifications are identified by a specific color on the architectural plan (anesthesiologist: blue, perfusionists: green, nurses: tan, and surgeons: purple), whereas the density of the line color indicates the frequency of movement within the time period studied (operative for this example).

The path width remains constant and reflects the physical path of movement rather than the frequency of movement or link as indicated in traditional link analysis diagrams. Zones highlighted in red physically identify and locate areas of density in flow disruption related to the physical space, layout of equipment, cabling, and tubing. This diagram illustrates a density of flow disruptions in the anesthesiologists and perfusionists primary work zones during this phase of the procedure.

**Discussion**

At a minimum, surgical flow disruptions extend surgeries and exacerbate ever increasing healthcare costs. More importantly, surgical flow disruptions can lay the foundation for errors. Consequently, the ability to classify disruptions in a systematic...
manner is critical if we are to identify areas for improvement, modification of OR design, or to focus future research efforts.

In this study, we were able to leverage the expertise of human factors engineers, healthcare architects, and cardiovascular anesthesiologists to systematically observe 10 cardiac procedures for flow disruptions. Unique to this study was the use of specific architectural layouts of the OR and equipment at each phase of surgery, which allowed the RIPCHORD study group to identify specific flow disruptions and tag them to a fixed location in time and space (fig. 4). Over 1,000 individual flow disruptions were identified and further organized into six distinct categories. The six distinct disruption categories were communication, environmental hazards, equipment failures, general interruptions, physical layout, and usability, and further subdivided into 33 subcategories.

Communication flow disruptions have traditionally received the greatest research focus due to the perceived ease of effecting lasting changes though staff retraining with methodologies successfully used in other domains such as Crew Resource Management. Furthermore, retraining workers is often seen as being less expensive than renovating facilities or upgrading equipment.

In our study, the majority of the communication disruptions occurred during the operative phase. Not surprisingly, many of these involved communication with surgeons. Because poor communication can have significant adverse effects on patient outcomes, it is critical to develop a robust subcategory taxonomy that recognizes the sometimes subtle differences between underlying causes. For example, lack of response and environmental noise are different even though the symptoms might appear similar. In our evaluation, communication flow disruptions accounted for less than a sixth (162 [15%]) of the total flow disruptions.

By using the detailed architectural diagrams, we were able to demonstrate the unique role that OR design and equipment layout has on the generation of physical layout flow disruptions. The physical layout category accounts for the OR personal’s interaction with the furniture, equipment, and use of the OR design space.

Our graphic analysis methodology (fig. 4) allows one to locate flow disruptions in space and visualize the largest physical layout subcategory observed—the density of equipment and inadequate allocation of space—which leads to the congestion of walkways and specific personnel areas. Having excessive personnel in the perfusion or anesthesia area limits personnel’s mobility and creates unwarranted conversations. Other worrisome physical layout subcategories include the positioning of equipment and connecting wiring and tubing between equipment and between equipment and overhead booms. Technological advances such as wireless data transfer would allow for the elimination of monitoring wiring and hence decrease the incidence of personnel slips and falls.

Flow disruptions interrupt the natural course of events in the OR and thereby have the potential to distract or divert personnel from the task at hand and may ultimately introduce errors and other threats to patient safety. The nine general interruptions subcategories account for 24% of the total flow disruptions. Education regarding OR policies and patient safety concerns may have a large impact on reducing this category of flow disruptions because shift changes, outside distractions, pages, teaching moments, and phone calls represent the majority of preventable disruptions in this category (table 3).

Given the inherent threat interruptions have on surgical flow, it is reasonable that any intervention or mitigation...
strategy might begin with this category as these are often “low hanging fruit.” For example, shift changes are often unavoidable but can be minimized by delaying breaks or lunches to times that have little impact on the case—when providers mental workloads are at the lowest points such as skin closure rather than on cardiopulmonary bypass.29 Phone calls and pagers should be signed out to other providers not responsible for the care of the patient in the OR. Closed circuit televisions and operative head cameras can be used to provide an optimized learning experience for trainees of all types in a remote location where they are free to ask questions and make comments that do not disrupt OR flow.

Usability is perhaps the most intuitive of disruptions and arguably one of the more frustrating as most health-care providers have been forced to operate machinery and tools designed by nonhealthcare professionals. Within our framework usability included problems associated with the use of technology, equipment, surfaces, physical barriers in the OR, noncomputer data entry (forms), or packaging of materials used in the OR. The usability of equipment, and surfaces, is the largest producer of flow disruptions in this category. Because OR personnel are highly trained, an outside observer would not expect this category to account for 20% of all flow disruptions. This category may be amendable to improvement through the use of staff education, training, and simulation exercises.30–33 Clearly, encouraging manufacturers to work with front-line providers when equipment is designed could significantly reduce these disruptions.

Environmental hazards, which disproportionally affect perfusionists, accounted for 8.5% of all flow disruptions and appeared more commonly during the preoperative and operative than the postoperative phase. This is largely due to the fact that over two thirds of environmental hazards are classified as slips or falls. Although relatively infrequent, but more alarming, was the fact that we documented six

Fig. 4. Architectural flow diagram. Architectural plan indicating composite staff movement during the operative phase of observed procedures. The personnel are identified by a specific color (anesthesiologists are denoted in blue, surgeons in purple, nurses in tan, and perfusionists in green). Each representation of a person indicates locations they have traveled, not the total number of people involved in the surgery. The density of the line color indicates the magnitude of movement within the time period studied. Red zones indicate areas with a high density of flow disruptions.
individual encounters with sharp objects (needles, scalpels) despite only observing 10 cases. Such threats to OR personnel are significant and suggest that although all personnel are trained on the proper use and disposal of sharps, they continue to be a problem in even the most vigilant OR environments.

The least common flow disruption was equipment failures. This mirrors longtime findings in the field of aviation safety, which determined that the overwhelming majority of accidents have been caused by human factors issues and not mechanical failure.34–36 Even so, equipment failure should not be ignored, as the consequences can be immense.

In sum, the RIPCHORD observational process was able to identify flow disruptions through direct observations and the use of architectural diagrams within the OR. To date, several processes have been proposed to study adverse events in health care, but none have identified flow disruptions in space. Human Factors Analysis and Classification System is a retrospective evaluation tool used to identify both latent and active failures. Once an accident occurs, evidence is gathered in an attempt to recreate the conditions immediately before the accident. Our classification system and Human Factors Analysis and Classification System is based on a Reason Swiss Cheese Model common framework describing how both latent and active errors align to result in an adverse event.37 In distinction to Human Factors Analysis and Classification System, RIPCHORD uses a prospective methodology to identify process failures.

Another evaluation process developed by Johns Hopkins Armstrong Institute of Patient Safety in partnership with the Society of Cardiovascular Anesthesiologists’ Flawless Operative Cardiovascular Unified Systems project is called the Locating Errors through Network Surveillance study.10 Similar to RIPCHORD, these researchers used multiple observers in the OR to observe and note defects. The observations were categorized using the Systems Engineering Initiative for Patient Safety model as a reference framework.38,39 Unlike RIPCHORD, their methodology used observers from different disciplines (clinicians, sociologists, and human factors engineers). As a result, many, but not all, errors that were noted resulted from noncompliance with known best medical practices. In contrast, RIPCHORD used only human factors trained experts and not clinicians as observers. Therefore, all our observations are related solely to flow disruptions and not medical best practices, which might change as new knowledge is acquired. RIPCHORD’s concentration on the human factors elements has resulted in a more simplified yet robust classification system for flow disruptions which may be applicable across all surgical disciplines. The application of this methodology in other disciplines in other ORs will need further study.

Despite clearly being able to identify flow disruptions in space and time, one limitation of our study is that we did not measure the duration and impact of each flow disruption. We cannot draw conclusions about the severity of each disruption or its impact on an operation. No patient data were collected, therefore there is no link exists between these reported disruptions and patient outcomes.

Methodology is currently under development which will enable researchers to understand the impact of each flow disruption. Further study will require researchers to examine the influence of a given flow disruption on the surgical staff by measuring the length of the disruption, the impact on the surrounding team, whether it is directly linked to an overt error, and the mental effort required by the provider to overcome the distraction. Notably, the latter poses the largest challenge to data collection given the intrusiveness of the potential measurement.

We know from other studies that any number of minor events in a case negatively influences a provider’s ability to compensate for subsequent major events.29 The most seemingly trivial disruption matters.

**Conclusion**

Over 1,000 individual flow disruptions were identified and further organized into six distinct categories including communication, environmental hazards, equipment failures, general interruptions, physical layout, and usability. These categories were then further divided into 33 subcategories. By using the detailed architectural diagrams, we were able to clearly demonstrate for the first time the unique role that OR design and equipment layout has on the generation of physical layout flow disruptions. The RIPCHORD study group has developed a robust taxonomy to describe the quantity and location of flow disruptions encountered in a cardiac OR which can be used for future research and patient safety improvements.

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**References**


