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Development of an Emergency C-Section Facilitator Using a Human-Machine Systems Engineering Approach

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Abstract

This paper describes the human-machine systems engineering process used to develop a prototype mobile communication and information system to facilitate preparation for emergency Caesarean sections in a rural hospital. The development team of engineering students, faculty, physicians, and nurses conducted a hierarchical process analysis to survey the problem scope and to develop functional requirements. A prototype, implemented systematically to meet those requirements, consists of a computer server, tablet PCs, and PDAs connected by a wireless network, which can be easily extended to a cellular network. The system summons the medical team via mobile devices and facilitates preparation of the patient, team, and operating room, and communication of their status. Evaluation of the system at the hospital yielded favorable responses and recommendations for enhancements.

Keywords
Human Factors, Health Care, System Design

1. Introduction
Time is of the essence after a decision is made to conduct an emergency medical procedure in a hospital. Preparation time is needed to summon, assemble and prepare the surgical team, as well as to prepare the patient, operating room and other support teams and facilities. For rural hospitals, assembling the team is particularly challenging since many of the required medical staff may be off-site, especially on nights and weekends. Even though these staff members are on call, critical time often includes the time for the hospital to contact the individuals and for the individuals to respond. In the meantime, on-site staff must quickly prepare the patient and operating room.

A team of industrial engineering graduate students and faculty at Oregon State University, with access to and support of subject matter experts from hospitals and a health insurance company, developed a communication and information system to support preparation for emergency Caesarean sections (C-sections) at a small rural hospital. The purpose of this system, called the **C-section Facilitator**, is to facilitate preparations for the emergency medical procedure. *The goal is to reduce the preparation time through improved efficiencies in the processes and to improve the readiness state through improved accuracies in completing all required process steps.* Although this system is designed for C-sections, the concept and system architecture are adaptable to other emergency surgical procedures.

Background information motivating the development of the system is provided in Section 2. The human-machine systems engineering approach to analyze, design, implement, operate, and evaluate the first prototype system is described in Section 3. The most recent prototype design and evaluation are presented in Section 4. Finally, conclusions and follow-on actions are summarized in Section 5.

2. Background
Urgency is vital for emergency C-section operations. Once the decision is made to conduct a C-Section, the goal is to deliver the baby within 30 minutes to minimize risks to both the mother and child. This goal places intense time pressure on the preparation and surgical teams. This time pressure, in combination with system vulnerabilities and intrinsic human fallibilities, increases the risk of an adverse outcome.

System vulnerabilities that contribute to the risk of adverse events include the physical condition of the mother and fetus, at least one of which is stressed; inherent risks of the C-section procedure, including blood loss and potential damage to adjacent organs; the time to notify and assemble the medical team, many of whom may be off-site since

emergency C-sections may occur at any time of day or night; communication difficulties among team members and support staff that are at times widely dispersed; and lacking, sub-optimal, or undocumented preparation processes. Human fallibilities that contribute to the risk of adverse events include the surgical team's limited attentional resources and capabilities, limited sensory abilities, working and long-term memory limitations, decision biases, motor limitations, and susceptibility to fatigue and other stressors.

A statement of need for the information system was prepared for the development team to minimize the risk of system vulnerabilities interacting with human fallibilities and resulting in significant human errors. Per the statement of need, the information system is to facilitate notification and assembly of the C-section surgical team; preparation for the mother and fetus, the surgical team, and the operating room; team communication; team awareness of system state and process status; and coordination of processes throughout preparation for the C-section. In addition, the system should be easily usable and learnable plus robust and reliable in the hospital environment.

3. Human-Machine Systems Engineering Process and First Prototype

To meet the statement of need, the development team applied a human-centered systems engineering approach to analyze the system processes, functions, and tasks; perform a basic and detailed design; implement the design with prototypes; simulate operations with scripted scenarios; and evaluate the system with the participation of key users. One of the success factors for this design process was to involve the users early in the analysis process, during the design development and implementation process, and at the final stages with the user evaluation. For this effort, the key users comprised medical staff (doctors and nurses) from two hospitals and one insurance company for healthcare providers.

Initially, the human factors engineering team established a knowledge base in C-section procedures, user needs, problems, and opportunities to facilitate preparation for C-sections. This phase consisted of literature review as well as presentations by and interviews of two obstetricians, one anesthesiologist, delivery nurses, and insurance company experts. Two hospitals were toured to learn about patient and operating room preparation processes.

To systematically develop C-section Facilitator requirements, the development team performed system and process analyses with key user participation. The system hierarchy model consisted of descriptions of the systems at the highest level with subsystems broken down at lower levels. Similarly, the process analysis, utilizing an approach similar to hierarchical task analysis [1] [2], yielded a model with the most general processes at the highest level followed by more detailed processes, functions and tasks at subsequent lower levels. See Figure 1 for the process model. Since such a model does not explicitly represent process or task interrelationships, which were necessary for the development of C-section Facilitator requirements, the team used Integrated Definition Language Ø (IDEFØ) [3] to capture and represent such knowledge. Figure 2 shows the IDEFØ model of the *Prepare for CS* process.

Because of limited resources and time constraints, the team focused on the first three process boxes in Figure 2: *Prepare team*, *Prepare patient*, and *Prepare OR (operating room)*. These three processes encompass the primary preparation tasks that are on the critical path prior to conducting the C-section procedure. Three sub-teams, corresponding to each of these processes, plus a fourth sub-team for system integration, were formed to complete process modeling and to conduct system development.

The lengthy modeling step was performed to develop a shared understanding among the team and users of the system plus the user's needs and to write system requirements. These requirements were documented in a spreadsheet workbook and organized according to the process hierarchy. Establishing requirements was an iterative and an evolving process.

The design phase for the initial prototype consisted of the three sub-teams developing design features and presenting those on paper or slides for the entire team to review and provide feedback. The integration team combined the sub-team's input, along with user feedback obtained from hospital staff, to implement the features into a single coherent design. The first prototype was an "electronic storyboard", consisting primarily of hypertext documents on a laptop computer and projector. Operation of the first prototype followed a scripted scenario with typical problems encountered during the preparation for an emergency C-section. This prototype was later evolved into a second prototype, to be described in Section 4, for which a usability evaluation was performed with the hospital staff.

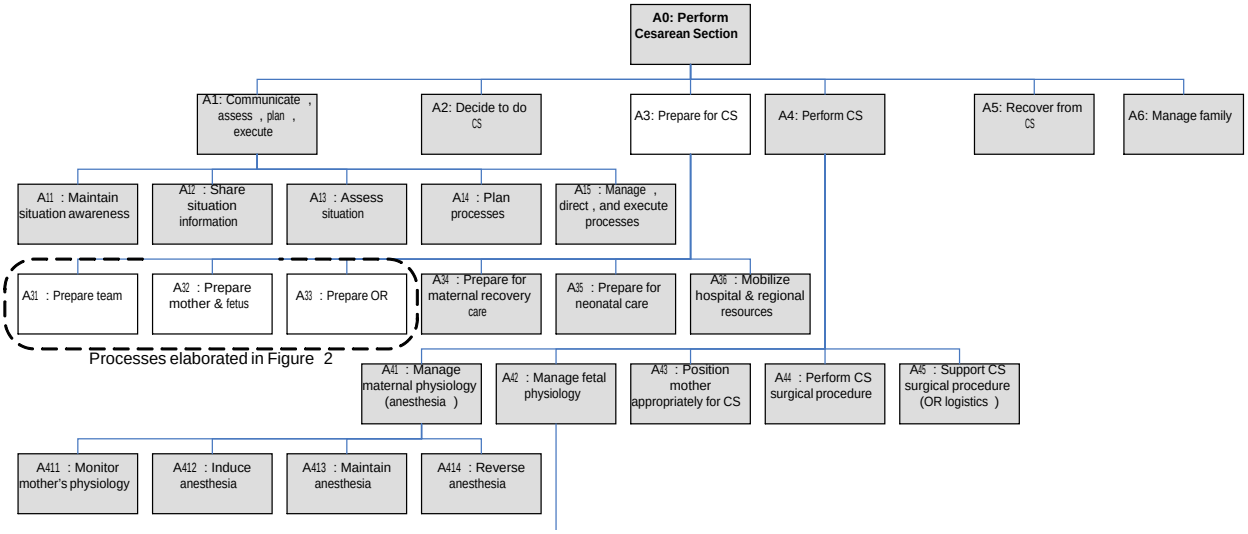


Figure 1: Part of the top-level of the emergency C-section process hierarchy model

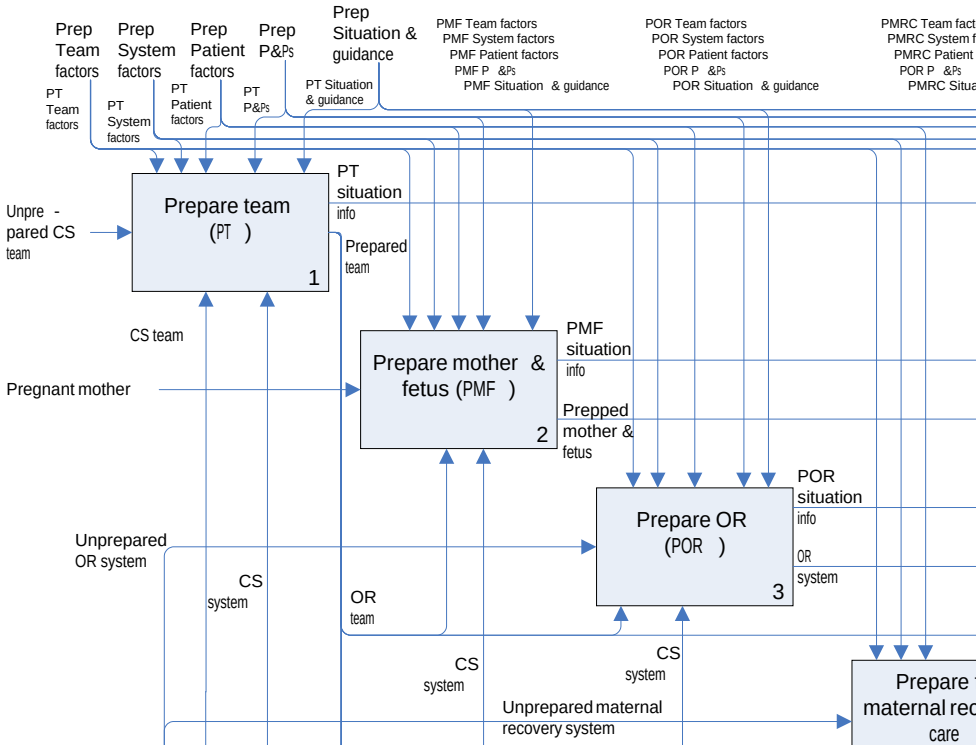


Figure 2: Part of the IDEFØ model of the *Prepare for CS* (C-section) process (white boxes if Figure 1), showing interrelated subprocesses. Boxes represent subprocesses that transform inputs (arrows entering from the left sides of the boxes) to outputs (arrows exiting from the right), subject to controls (arrows entering the top). Subprocesses are performed by mechanisms (arrows entering from the bottom), in this case, human actors.

4. Second Prototype

The second and most recent prototype consists of a computer server, tablet PCs, and PDAs connected by a wireless network. Figure 3 illustrates the system architecture and sample screenshots. The computer server provides the C-section related information to workstations or laptops and monitors located in the hospital. A workstation is

employed by the ward clerk to enter the summons data and initiate the pages to the on-call medical staff. The workstations and monitors also display the status of the patient (including updated medical data) and the preparation status of the surgical team, patient, and operating room. The tablet PCs are used primarily to input updated patient medical data directly into the database on the server. PDAs are the mobile devices that off-site medical staff possess for notification by the C-section Facilitator summons process and for response indicating their availability. The PDAs also allow access to the patient medical data and the preparation status of the team, patient, and operating room via password authentication.

The prototype software uses ASP.net to create dynamic contents in displays. Cascade Style Sheets (CSS) are used to display data in different but consistent formats corresponding to the display devices. A database is maintained in Microsoft Access format to store the patient data and on-call lists of medical staff. In addition to the hardware devices shown in Figure 3, the final system is designed to utilize an automatic paging system to dial numbers for the PDAs or smart phones on a cellular network, and to broadcast notification messages simultaneously. This device will provide significant time savings to notify the medical team, as the pages are currently done in series by a single ward clerk. The displays for the preparation status of the surgical team, patient, and operating room are designed to be touch-screen monitors. This will expedite updating of each status by touching the status icon on the screen rather than entering the data with a keyboard or mouse. The final prototype will be implemented to utilize the automatic paging system and touch-screen monitors.

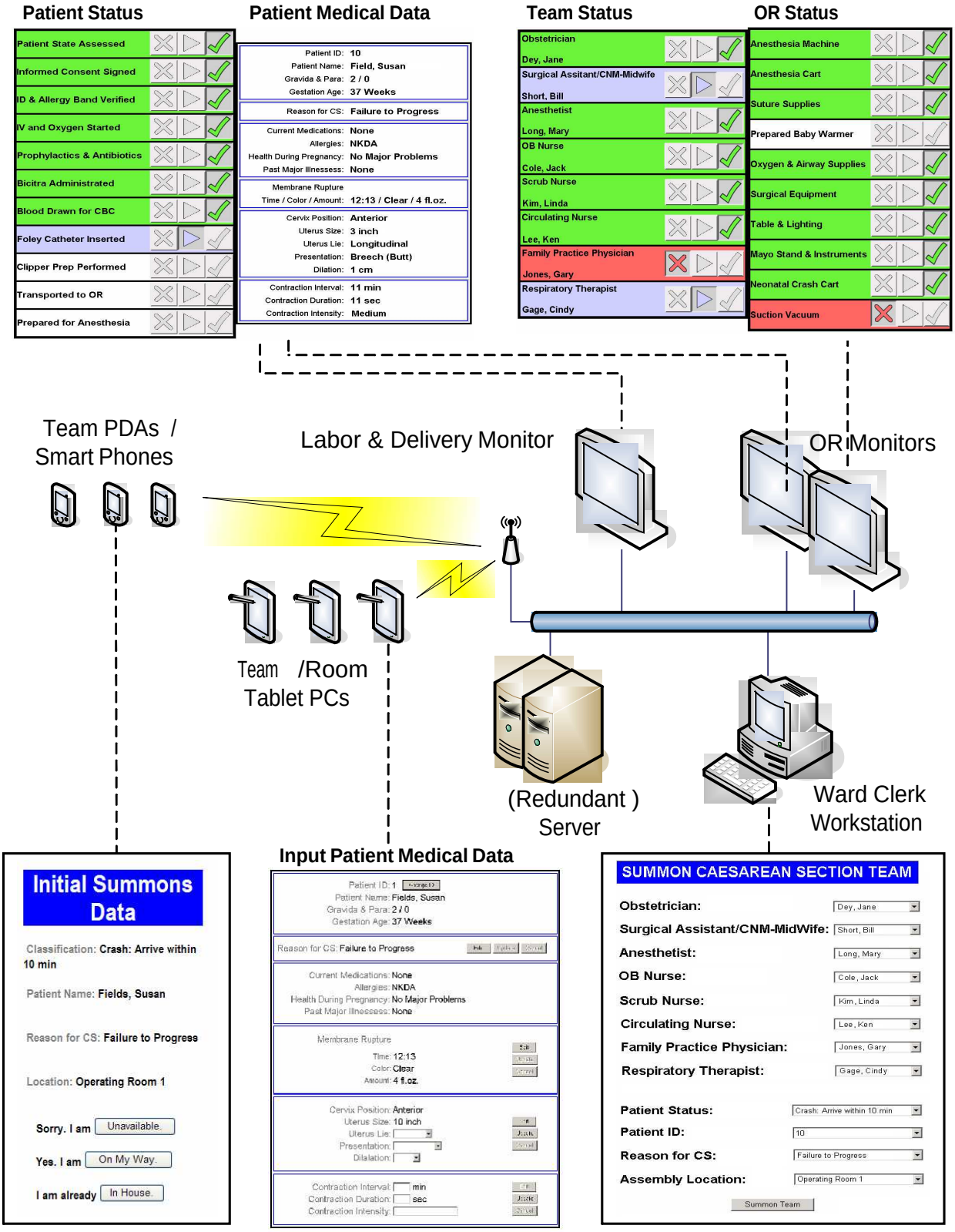
The C-section Facilitator is initiated immediately after the decision to proceed with an emergency C-section. The ward clerk begins the team notification process with the initial summons screen shown in Figure 3 to contact the staff members on call. The database contains the on-call staff members in the order of first to last responder. The clerk can use the drop-down menu to select other staff members on the on-call list if the first provider is unavailable.

The initial summons screen includes four other items of information that can be input via the clerk's drop-down menu. The first two items are the patient status and identification. The third item of information is a brief reason for the emergency C-section. The final item is the location to report for the C-section procedure. This minimal necessary data is provided with the initial summons to minimize the time to enter the data and the time to read the information. After the initial summons screen is completed, the ward clerk clicks on the submit button and the C-section Facilitator broadcasts the summons data to PDAs or smart phones of the first on-call team members.

The on-call staff receives the initial summons to report via a PDA with the screen depicted in Figure 3. The receiver has three options to respond: "unavailable", "on my way", and "in house." If the first on-call staff member responds as unavailable, the C-section Facilitator proceeds to the second call-out person for that function, while notifying the ward clerk. If the first on-call staff member does not respond within three minutes, the C-section Facilitator flags this as a problem on the prepare team status screen (to be described below). The C-section Facilitator continues to dial the first on-call responder until five minutes after the initial summons is sent. After five minutes, the C-section Facilitator starts to page the second staff member on call for that function and so notifies the ward clerk. This process is repeated on five minute intervals until someone responds positively or until the call-out list is depleted.

Using the PDAs, the available on-call staff members relay status updates to the C-Section Facilitator when they are on the way to the hospital and when they have arrived at the hospital and are ready for the C-section. These updates are displayed on the team status screen shown in Figure 3. The display provides a list of surgical team members and names, with three columns identifying each status as problem, in-transit, or ready. Button icons for these three states are shown for each team member as an x, > , or ✓. These button icons are activated via the PDA or the ward clerk pushing the icon button on the touch-screen display to display the status of each team member. The icons and rectangular areas for each team member are redundantly color-coded. Initially this display starts out as white when the summons calls are first made. After three minutes, the icon and rectangular area for a team member turns red if that team member has not responded, thereby indicating a problem. The colors are a neutral blue-gray when the provider is in-transit. The icon and rectangular area turns green when the team member is at the hospital and ready. Thus, it is readily apparent by glancing at the display screen which team members have not reported (problem), are on their way (in-transit), or are at the hospital and prepared (ready).

As shown in Figure 3, a similarly formatted screen is used to facilitate preparation of the operating room (OR). This display includes all the critical process steps to properly configure the OR for the C-section. These critical process


Patient Status
Patient State Assessed
Informed Consent Signed
ID & Allergy Band Verified
IV and Oxygen Started
Prophylactics & Antibiotics
Bicitra Administrated
Blood Drawn for CBC
Foley Catheter Inserted
Clipper Prep Performed
Transported to OR
Prepared for Anesthesia
Patient Medical Data
Patient ID: 10
Patient Name: Field, Susan
Gravida & Para: 2 / 0
Gestation Age: 37 Weeks
Reason for CS: Failure to Progress
Current Medications: None
Allergies: NKDA
Health During Pregnancy: No Major Problems
Past Major Illnesess: None
Membrane Rupture
Time / Color / Amount: 12:13 / Clear / 4 fl.oz.
Cervix Position: Anterior
Uterus Size: 3 inch
Uterus Lie: Longitudinal
Presentation: Breech (Butt)
Dilation: 1 cm
Contraction Interval: 11 min
Contraction Duration: 11 sec
Contraction Intensity: Medium
Team Status
Obstetrician
Dey, Jane
Surgical Assitant/CNM-Midwife
Short, Bill
Anesthetist
Long, Mary
OB Nurse
Cole, Jack
Scrub Nurse
Kim, Linda
Circulating Nurse
Lee, Ken
Family Practice Physician
Jones, Gary
Respiratory Therapist
Gage, Cindy
OR Status
Anesthesia Machine
Anesthesia Cart
Suture Supplies
Prepared Baby Warmer
Oxygen & Airway Supplies
Surgical Equipment
Table & Lighting
Mayo Stand & Instruments
Neonatal Crash Cart
Suction Vacuum
Team PDAs / Smart Phones
Labor & Delivery Monitor
OR Monitors
Team /Room Tablet PCs
(Redundant) Server
Ward Clerk Workstation
Initial Summons Data
Classification: Crash: Arrive within 10 min
Patient Name: Fields, Susan
Reason for CS: Failure to Progress
Location: Operating Room 1
Sorry. I am Unavailable.
Yes. I am On My Way.
I am already In House.
Input Patient Medical Data
Patient ID: 1
Patient Name: Fields, Susan
Gravida & Para: 2 / 0
Gestation Age: 37 Weeks
Reason for CS: Failure to Progress
Current Medications: None
Allergies: NKDA
Health During Pregnancy: No Major Problems
Past Major Illnesess: None
Membrane Rupture
Time: 12:13
Color: Clear
Amount: 4 fl.oz.
Cervix Position: Anterior
Uterus Size: 10 inch
Presentation:
Dilation:
Contraction Interval: min
Contraction Duration: sec
Contraction Intensity:
SUMMON CAESAREAN SECTION TEAM
Obstetrician: Dey, Jane
Surgical Assistant/CNM-MidWife: Short, Bill
Anesthetist: Long, Mary
OB Nurse: Cole, Jack
Scrub Nurse: Kim, Linda
Circulating Nurse: Lee, Ken
Family Practice Physician: Jones, Gary
Respiratory Therapist: Gage, Cindy
Patient Status: Crash: Arrive within 10 min
Patient ID: 10
Reason for CS: Failure to Progress
Assembly Location: Operating Room 1
Summon Team

steps were determined from the hierarchical process analysis described in Section 3. In addition to displaying status, this screen display serves as a memory aid to remind the responsible staff of the critical items needed to prepare the OR for a C-section. The icons and color coding are similar to those described above, but gray-blue indicates a process in progress and expected to be completed without problems, and green indicates that the particular system or equipment is ready. White background and monochromatic icons indicate preparations have not been started.

The other screenshot shown at the top of Figure 3 is for the patient preparation process with updated patient medical data. The process preparation steps shown were determined from the detailed hierarchical process analysis described in Section 3. Identical color coding and icons are used as in the OR screenshot. To update the patient medical data, a tablet PC is employed, thereby avoiding paper recording or keyboard entry. As shown at the bottom of Figure 3, the tablet PC screen is used to facilitate input of the data with drop-down menus. The patient, team and OR status displays in Figure 3 are also available on the PDAs.

The second prototype was demonstrated to hospital staff to solicit feedback on the usability and effectiveness of the C-section Facilitator, primarily with respect to efficiency, learnability, memorability, and satisfaction. The scripted scenario for this initial usability test included three problems: 1) failure of a team member to respond in a timely manner, 2) miscommunication of an assigned task which is subsequently not done, and 3) problem with equipment in the OR. The screenshots at the top of Figure 3 illustrate how the C-section Facilitator readily communicates the status of these issues. The non-reporting staff member is highlighted in red along with the problem icon; the baby warmer is still displayed in white indicating that the preparation process has not begun; and the vacuum is shown in red signifying a malfunction. All other items are green for complete or gray-blue for in-transit or in-process without problems expected. The C-section Facilitator thus provides readily discernable status displays in key locations within the hospital to highlight these problem areas, thereby attracting attention for prompt action or recovery.

In general, positive comments were received concerning the second prototype system. All participants agreed that the C-section Facilitator had the potential to reduce preparation times for emergency C-sections through streamlined communications and to improve the readiness state in terms of accuracy by serving as a memory aid.

5. Conclusions

The second prototype meets the statement of need to facilitate team communications and preparation activities for emergency C-sections. The C-section Facilitator is anticipated to reduce the time to assemble the medical team due to the simultaneous broadcast of the initial summons information and the ability of PDAs to succinctly communicate information to the on-call medical staff and in turn for the staff to promptly reply. The status screens for the medical team, patient, and operating room facilitate communications, thereby minimizing the need to ask questions on progress and thus interrupting preparation tasks. The status screens also serve as memory aids to minimize the risk of human error due to forgetting task steps during high stress conditions under extreme time pressures.

The first usability test performed at the hospital yielded favorable responses. Based on feedback from this test, follow-up improvements to the prototype include adding drop-down capabilities for status screens to provide troubleshooting steps or reasons for a problem and making patient medical data more “dashboard” like by clustering related information. Hardware also needs to be added to the prototype design to enable the automatic paging capability and touch-screen displays. The next prototype also should be extended to a cellular network and additional usability tests should be performed under more complex test conditions.

Finally, future efforts can also explore adapting the C-section Facilitator to other emergency surgical procedures.

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References

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