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ORIGINAL ARTICLE

A computerized perioperative data integration and display system

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Abstract *Object* The operating room is rich in digital data that must be rapidly gathered and integrated by caregivers, potentially distracting them from direct patient care. We hypothesized that current desktop computers could integrate enough electronically accessible perioperative data to present a unified, contextually appropriate snapshot of the patient to the operating room team without requiring any user intervention.
Materials and methods We implemented a system that integrates data from surgical and anesthesia devices and information systems, as well as an active radiofrequency identification location tracking system, to create a comprehensive, unified, time-synchronized database of all digital data produced by these systems. Next, a human factors engineering approach was used to identify selected data to show on a large format display during surgery.
Results A prototype system has been in daily use in a clinical operating room since August 2005. The system functions automatically without any user input, as the display system self-configures based on cues from the primary data. The system is vendor agnostic with respect to input data sources and display options.
Conclusion Automatic integration and display of team-synchronizing data from medical devices and hospital information systems is now possible using software that runs on a personal computer.

Keywords Data integration · Operating room · Status display · OR black box recorder · Surgery team

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Introduction

Surgery is a complicated event, and the efficient and safe functioning of an operating room (OR) depends on the coordinated action of the OR team. The physicians, nurses, technicians, and other personnel who comprise the OR team have a multitude of tasks, and need ready access to information about the patient and about the status of the perioperative system. In addition, the emergence of high throughput operating rooms [1–7] has amplified time constraints, requiring a solidified culture of teamwork to facilitate increased throughput while maintaining patient safety. Thus, 'just-in-time' delivery of key patient information from many disparate data sources, and integrating it on a single, cohesive display could give each team member the same perspective on each patient without interrupting their work, and this might be beneficial to OR efficiency and patient safety.

Fig. 1 Example of the myriad data sources incorporated by the anesthetist (*top*), surgeon (*middle*) and nurse (*bottom*) to synthesize their view of the patient and the state of the operation. Note the multiple displays, and that most are positioned so that they are only readily visible to a few individuals

Typically, the hospital information systems, monitoring systems and treatment delivery systems in the OR do not communicate with each other. Consequently, fragmentation of data divides the team's attention among multiple displays, as evidenced in Fig. 1. Here, the anesthesiologists, surgeons and nurses interact with many separate displays, each attached to its own individual computer, to provide physiologic monitoring, automated anesthesia record keeping, drug infusion, patient warming, hospital information system access, order entry, drug/supply chain management, surgical instrument control and clinical documentation. This creates a situation where different team members have different information 'snapshots' of the same patient. Each individual in the room may hold critical but only partially overlapping information about the case or patient [8].

In addition to the fragmentation of resources and displays, time and effort are spent unnecessarily logging-on to each separate display, potentially multiple times during a single case. The time expended on computer interfacing redirects the caregiver's attention away from the patient, which interferes with the flow of work [9] and potentially increases the risk of missing a critical event.

The multiple computer systems are meant to provide information to OR team members, but the information must be communicated throughout the team to be optimally useful. Ineffective communication can be a significant barrier to operative and perioperative efficiency, situational awareness and safety. Over a third of communication failures in the operative environment result in visible effects on system processes, including inefficiency, team tension, wasted resources, delays, patient inconvenience, and errors [10], which, in turn, may lead to decreased patient safety. Many communication failures occur due to suboptimal timing of information exchange, when information is requested or provided too late to be optimally useful [10]. The deployment and use of information displays targeted at the entire OR suite might be expected to improve management of patient preparedness and equipment readiness, diminish the occurrence of adverse events related to poor information, and minimize interruptions in the OR team's workflow by delivering patient and system information at the point of care. A recent study demonstrates that this work is currently performed by individuals [11], and these communications are subject to frequent interruption [9].

Thus, a real-time integrative display of team synchronizing data- that is, preoperative and operative data aimed to ensure that all members of the OR team hold the same basic information, might improve OR communication, team performance, OR efficiency, and patient safety by increasing situational awareness[1] [12]. However, before these possibilities can be explored, we must first determine whether such a system can be created in a clinical OR using currently available technology. If such a system can in fact be created, it would be more likely to gain wide acceptance if it were inexpensive and if it imposed no additional work on users. Against this background, we hypothesized the following:

1. That advances in available computation power, network bandwidth and storage capacity, along with useful

[1] Anesthesia information management systems provide a degree of integration and synchronizing information, but their output is geared solely to anesthesiologists.

Table 1 Medical equipment interfaced to the display system

Manufacturer	Device name/ model	Purpose	Digital output	Digital communication protocol
GE	GE Solar 8000 M	Physiologic monitor	Ethernet/serial	GE Proprietary
GE	TRAM	Vital signs acquisition	to Solar 8000 M	GE Proprietary
GE	SAM	Breathing gas composition	to Solar 8000 M	GE Proprietary
Philips	All models	Physiologic monitor Vital signs acquisition	Ethernet	IEEE 1073
Drager North America	Apollo	Anesthesia machine	Serial	Medibus—Drager Proprietary
Aspect Medical	BIS monitor	Level of consciousness monitor	Serial	Aspect Medical Proprietary
Karl Storz	Insufflator	CO_2 insufflation of abdomen	SCB	Storz Control Bus—proprietary, based on CAN
Karl Storz	Hysteroscopic fluid management system	Monitoring admin/recovery of fluid	SCB	Storz Control Bus—proprietary, based on CAN
InstruMed	SmartPump	Tourniquet	Serial	Proprietary Protocol

Abbreviations: BIS Bi-spectral index, *SCB* Storz Control Bus, *CAN* controller area network

developments in standardization of communication protocols between medical devices, were sufficient to allow the development of a practical, personal computer-based integration system encompassing all of the digital data in the operating room.

2. That data from this integration would be usable to create a large format display of the basic team-synchronizing data needed about the patient.
3. That there were sufficient signals generated in the OR environment, either from automatic systems or as part of routine activities, to keep the data display synchronized to the stage of the perioperative process, thereby providing contextually relevant information throughout an operative case without any need for human input.

In this paper, we describe the initial implementation of such an integrated perioperative data display system, starting with the initial specifications and concluding by describing the functionality of the working prototype.

Material and methods

The project was undertaken in the operating room of the future (ORF) at Massachusetts General Hospital (MGH). The ORF is typical of new operating rooms that are constructed to support minimally invasive surgery and of other ORF initiatives seeking to address the information needs of the perioperative team [13,14]. Like most newly constructed ORs, the ORF provides ample network access, including wireless capability, and multiple computerized information systems, as well as surgical and anesthesia systems that have on-board computers and machine-readable digital data output capability. This was a technology development project, but there were no changes in patient care relative to the standard patient care provided in other ORs. Furthermore, no new information about the patient was created by the system. Instead, the system re-displayed data that were already readily available, if not optimally displayed. For these reasons, the MGH Institutional Review Board deemed the project to be exempt from human subjects review.

The integrated display system described in this paper is one result from a project whose overall objective was to record and archive all of the digital data passing through the OR into a single, synchronized database. We began by searching for input data sources in the ORF. Equipment was catalogued and each device's communication capabilities were determined and recorded. Operating room administrative, patient care and hospital information systems were also catalogued and their interface capabilities determined. Tables 1 and 2 present summaries of the devices and information systems found within the ORF and other similar ORs at comparable hospitals.

Each device's communication protocol and data definition were analyzed to ascertain whether it could be read by a commercially available data integration system or whether a custom interface would need to be developed. Using the physiologic monitor as an example, we determined that the chosen integration software (LiveData OR RTI Server, LiveData, Inc., Cambridge, MA, USA) could capture all device data, including detailed physiological waveform data and all data elements, without data loss and in real time. Similar analyses were performed for data coming from the other OR equipment, as well as administrative, patient care, and hospital information systems. Where standard interfaces were available, they were used, although in many instances (see

Table 2 Hospital information systems interfaced to the display system

Manufacturer	System name	Purpose	Interface	Data available
Radianse Inc.	Indoor positioning system	Asset and Patient location	XML	Real-time location
Partners IS	Partners enterprise allergy repository	Patient drug allergy data	XML	Drugs provoking allergic reactions
				Nature of reaction
Partners IS	OR dynamic schedule	OR scheduling	XML	Scheduled OR
				Surgeon
				Patient name
				Planned procedure
				Laterality
				Periop milestones
Drager	Saturn	Anesthesia information management	XML	Anesthesia milestones
				Anesthesia drug administration
Epic	OpTime	OR Management	HL7	Surgeon
				Patient name
				Planned procedure
				Laterality
				Perioperative milestones
Cerner	CoPath System		HL7	

Abbreviations: XML extensible markup language, *IS* information systems, *OR* operating room

Tables 1 and 2) only proprietary communication protocols were used by the equipment manufacturers. Recording data from these systems required the development of custom interfaces. Each interface required between 5 and 15 person-days to develop using standard programming tools.

Several operating rooms at our institution are equipped with a location tracking system (Radianse, Lawrence, MA, USA) to track patients, assets and OR personnel [15,16]. The tracking system uses dual emission (active radiofrequency plus infrared light) technology to achieve room-level spatial and 10-s temporal resolution, with output via an extensible markup language (XML) remote procedure call messaging system. Patients and OR staff who are scheduled to be in one of the ORs with the location tracking system were tracked throughout the OR suite. Prior to developing the integration and display system described in this report, the only way to access the location data was to perform a search query using a Web interface provided by the tracking system vendor.

The integration system described in this paper uses the tracking data to populate a dynamic staff list included in the integrated OR information display. The list of personnel present in the OR is updated throughout the case; personnel no longer present are designated as such. Timestamps of tracking system events, such as changes in location, are stored in a structured query language database.

There are also several hospital information systems in the operating room suite. Our institution uses an internally developed computerized system called the nursing perioperative record for perioperative documentation including time stamps for key process milestone events. An OR Dynamic scheduling system receives data from the nursing perioperative record. The OR Dynamic system exposes nursing perioperative record data for each case including procedure, patient name and scheduling surgeon via an XML interface. An anesthesia information management system (Saturn, Drager North America, Telford, PA, USA) records anesthesia interventions, but without integration with other systems. Patient drug allergy data are obtained from a system-wide database called the partners enterprise allergy repository. An internally developed computerized provider order entry system forces recording of allergy information before patient orders can be written, ensuring that allergy data are available via the partners enterprise allergy repository.

The system was implemented on a fast, consumer-level personal computer (dual Xeon processors 3.06 GHz, 2 GB RAM), with a consumer-grade video card (Nvidia Quadro FX5200). Interfaces with each of the medical devices and information systems described above were developed, utilizing XML and HL-7 messaging where possible. No peripheral devices were required.

Human factor designers (Aptima, Inc., Woburn, MA, USA) and clinicians who would be the end users undertook a "human factors engineering" approach in designing the specifications of the integrated displays. This is an approach to medical system design that centers on the user and the workflow [17]. This approach focuses on factors such as the quality of user interface designs in order to enhance situational awareness, decrease the time to respond to critical

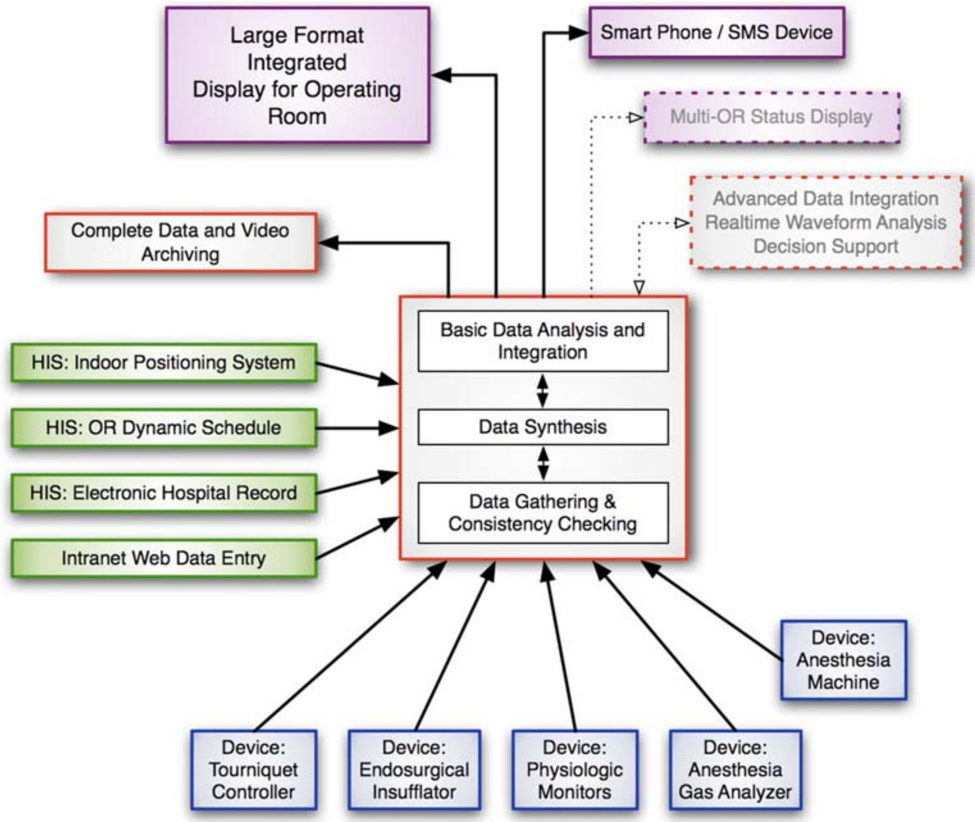

Fig. 2 Block diagram of the OR data integration and display system as currently deployed. All devices are connected to the integration computer by Ethernet connections. A subset of data are displayed on a large format screen for viewing by OR personnel. Functionalities that have not yet been enabled are shown with dashed lines and gray type

events, and to facilitate the access to critical patient information. With the possibility of information overload being an issue, the data selected to be displayed was chosen based on whether it was important for at least two members of the OR team (nursing, anesthesia, surgery) in order for them to fulfill their responsibilities and tasks in a safe and efficient manner. A multidisciplinary team of OR physicians and nurses, medical informatics experts and user interface designers then worked iteratively to create the prototype display.

Results

The proposed system was required to have three major capabilities derived from our original hypotheses: [1] complete data capture and recording from all OR devices that produce digital output, [2] a single integrated data display large enough to show selected patient data deemed critical by the clinicians who would use it and [3] ability to change the display to show contextually relevant information as the case developed without any requirement for user interaction. We tested our hypotheses by attempting to meet the system requirements in an installation deployed in a clinically working operating room. Figure 2 provides a block diagram of current devices integrated by the system and display and analysis capabilities that are in development.

Integration

Most of the OR devices that have digital user interfaces also have a digital output. Communication protocols have been obtained for all of the devices listed in Table 1. At the time of this report, data capture and integration for all devices except the infusion pumps has been achieved, and most are routinely displayed during each clinical case in which they are used.

As illustrated by Fig. 3, ORs do not exist as isolated domains in the hospital, but rather, are connected to hospital information systems. This connectivity is more apparent in the ORF, which consists of a suite of rooms clustered around a single OR, with a complex, interlinked workflow (Fig. 3). ORs receive valuable information from the HIS (e.g., patient history, allergy data, lab data, problem lists and process status data), and could potentially provide valuable OR process status data (e.g., surgery is running ahead of schedule) to

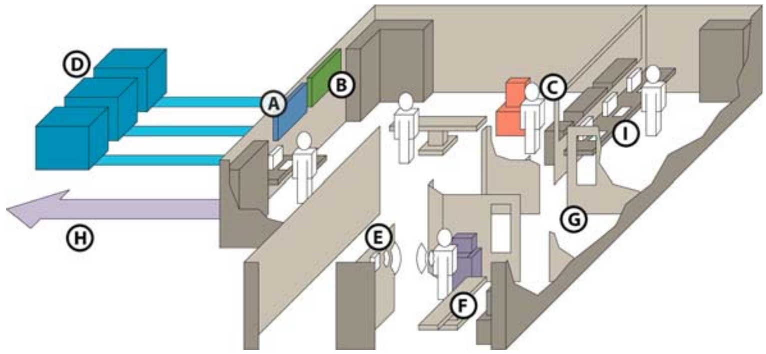

Fig. 3 The integrated information display (A), positioned directly adjacent to the surgical video display (B), collects information from a number of devices and information systems present within the operative suite (C) such as the physiologic monitor, surgical equipment, the anesthesia information management system and nursing perioperative record along with external information sources (D) including the partners enterprise allergy repository and OR dynamic scheduling system. A radianse location tracking system (E) also provides input to the system. Information sources from other areas of the operative environment, including the induction room (F) and early recovery area (G), also integrate into the system and provide valuable hooks into the operating room. Data created by the system, such as the imminent end of surgery deduced from entries into the OR computers and from OR equipment status changes, can ultimately be made available to other applications outside of the operative environment (H) or the system, as a whole, can be made available for viewing on a personal computer (I)

adjacent areas. At our hospital, most information systems were internally developed at different times to meet specific needs, and so presented something of an integration challenge. Nevertheless, data from the relevant systems listed in Table 2 are routinely integrated into the database and included in the integrated perioperative data display system.

The system was implemented on a personal computer using standard network and serial connections and standard storage media. For the medical devices and the HIS, the integration system consumes and archives the entire available data output. The available data transfer and storage bandwidth vastly exceed the system's requirements. For instance, a single electrocardiogram waveform contains 240 points per second, with each point being a 2-byte word, resulting in 480 bytes per second of data for the capture of this waveform. Current transfer rates of modern hard drives and interfaces are on the order of 150 MB, or 150,000,000 bytes, per second. Thus, individual waveforms are miniscule compared to storage transfer rate limits, theoretically allowing for the simultaneous capture and storage of several hundred thousand waveforms at a time. This number is further enhanced by data compression techniques that increase this theoretical limit.

Data are maintained in a relational database with an archive of all captured OR data, including trends and full resolution waveforms, information from the location tracking system, and patient and scheduling information. The database schema is determined automatically from the system configuration and takes the simple approach of creating one table per monitored data element. Each of these tables stores time stamps along with the data values. When collecting structured data, the structure fields are flattened into columns in the table. This automated database creation allows easy extensibility as new data sources are added to the system and allows time-based playback and analysis of the events of the surgery.

The database consumes less than 50 MB of storage space per hour of stored data. Data may be compressed at a 5:1 ratio and may feasibly be maintained indefinitely as our storage capacity and the need to retain a more complete patient record increase.

The capture of real-time waveforms from multiple monitors also does not utilize excessive network bandwidth or approach bandwidth limits. Sample waveform packets are almost 1 KB, or 1,000 bytes in size, and contain approximately ten waveforms of varying sizes. These packets are sent over the local area network at a rate of four per second. Therefore, the capture of data from a single physiologic monitor, represented by this packet containing multiple waveforms, results in approximately 4 KB, or 4,000 bytes, of network traffic per second. Utilizing 50% of a 100 megabit network switch, the system could capture data from over 1,500 individual monitors (representing over 15,000 waveforms per second) with modest network usage.

Thus, our results to date regarding technology capabilities do not negate the first hypothesis, and it appears that current technology was sufficient to achieve the desired level of integration.

Display of basic team synchronizing data about the patient

Prior to starting this project, the ORF already had a large aspect plasma screen display for viewing the surgical procedure (Fig. 4, right-hand side). This display allows all team members to view the surgery and be aware of surgical events. Institutional custom strongly opposed recording the surgical

Fig. 4 The integrated OR data display resides directly adjacent to the surgical display. The close proximity of two large displays mandated that the design avoid detracting from the pre-existing surgical display, which is often in use during cases. The surgical display provides the entire OR team with an overview of the surgical situation. The OR data integration system is designed to provide a similar overview for key patient perioperative data, including patient and staff identity, the procedure being performed and high-level physiologic trends. Thus, the system required adequate font size and graphical resolution to be visible and legible to anyone in the room, requiring the use of a large 42″ LCD display. Patient identifiers normally present on the display have been removed from this illustration

video, so it is neither recorded nor archived in our implementation of the integration system. However, the capability to record and archive digital video synchronized to the rest of the perioperative data is a part of the integration system and has been implemented at other sites.

The second display for the integrated perioperative data system is positioned directly adjacent to the already existing surgical monitor (Figs. 3, 4). Selection of the information to be shown on the integrated perioperative data display system was performed by a multidisciplinary team of all major stakeholders in the OR. All data displayed had to be relevant to at least two of the three main parties in the operating room (nursing, anesthesia and surgery). By ‘relevant’, we mean that it was agreed during the development process that the data were important for safety or efficiency in the OR. The system is required to avoid any manual data entry or additional work by OR team members.[2] Thus, all data shown by the display are automatically fed to the integration system from existing clinical computer systems or medical devices active within the operating room environment. When data were not received because OR workers did not input it into the primary devices, the dependent field in the integrated display remained blank.

Diagnostic images were not included in the initial system simply because they are rarely used in the demonstration test site (ORF). However, image integration is within the specification of the system and will be implemented when needed.

[2] Although prohibited in our specification, OR team members could, in principle, enter data directly into the system via a web interface. In our implementation, team members outside the OR update information about the patient in the immediate preoperative period using a web page.

The display itself is created using scalable vector graphics (SVG). As a result, the display may be viewed in any web browser that has the Adobe SVG viewer installed. SVG is an XML markup language for creating vector graphics and is an open standard created by the World Wide Web Consortium. This allows for changes to the system display to be implemented in a few days (crucial when prototyping from user feedback) and a sufficient degree of customizability to meet the needs of an OR display. Our approach enables arbitrary granularity in the number of display configurations, from having unique displays for each surgical team to having a single display standard for the entire institution.

Contextually driven automatic configuration of the display

The objective of the integrated perioperative data display system is to provide at-a-glance understanding of the patient and the case to complement the surgical status and progress information contained in the surgical video. As originally specified, all information displayed is automatically acquired; there is no manual data entry adding to the OR-based team’s workload. However, to change the information displayed to match the context as the case progresses, the integrated perioperative data display system contains a number of persistent and dynamically advancing elements based on the stage of the current case (see Figs. 5, 6, 7).

Persistent information panes are arranged framing the tabbed, dynamically advancing panes. Data displayed on the persistent panes (see Fig. 5) include: [1] patient demographics including name, age, weight, and medical record number, [2] patient allergies, [3] case information such as diagnosis, procedure, laterality, and type of anesthesia, [4] the OR room

Fig. 5 Screen capture of the integrated information display. The integrated OR data display consists of a group of persistent panes around the perimeter and dynamically advancing panes arranged by tabs (Case Setup, Time Out and Intraop) in the center. This figure highlights the contents of the "Case Setup" dynamic pane. Patient and staff identities have been concealed in this figure. Note the *white* text for the confirmed patient name and the *gray* text for the unconfirmed procedure

Fig. 6 Screen capture of the second dynamic pane (the "timeout" pane). Patient and staff identities have been concealed in this figure. Note that the procedure has now also been confirmed by the OR team and the font has automatically changed from *gray* to *white*

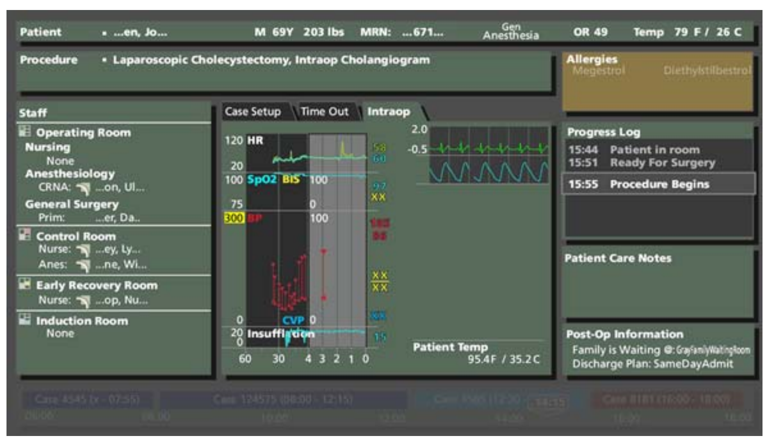

Fig. 7 Screen capture of the third dynamic pane (the "Intraoperative" pane). Patient and staff identities have been concealed in this figure. The active tracking system has mapped personnel to multiple spaces throughout the OR suite

number and current room temperature, [5] staffing information including nursing, anesthesia, and surgical teams, and [6] a case progress log. We have also implemented a timeline of the OR's progress through the day's cases, but this is shown in 'mock-up' form, grayed out on the bottom of Figs. 5, 6 and 7.

The persistent information serves to orient all members of the team to the patient, procedure, laterality and personnel during the case and during staffing changes. Some information, such as the patient's name and demographics, procedure and laterality, staffing list, allergies and the case progress log remain consistent across all stages of the case. Other information in the persistent panes may change, such as new events in the progress log or staffing changes updated via the location tracking system, but the panes themselves are always present and provide the same information fields.

The data presented in the staffing pane (see Fig. 4 for example) are ‘live’; that is, they are gathered and updated automatically from the location tracking system. Individuals whose names are bright white are actually present in the OR, while those whose names are grayed are not currently present. While it seems simple to determine which staff are in the OR by looking around, staff changes are not always communicated to the entire OR team. Many individuals at our institution have enthusiastically embraced the idea of displaying an automated staff list when they first encountered it on the integrated display.

The dynamically advancing panes are organized through a tabbed scheme at the center of the display to illustrate the current, prior, and future stages in the case progression. Tabs for the pre-operative case setup, the “time out” process, and the intraoperative time periods are loaded automatically based on the stage of the case. These are illustrated in Figures 5, 6 and 7. The data selected for display on each of the dynamic panes was judged by the user interface design group to be important for one stage of the case but dispensable during other stages. The stage of the case is deduced by the system from milestone data entered in the electronic NPR and from patient location data, and the display is automatically advanced to match the stage. Rather than requiring OR workers to have sufficient situational awareness to advance the display manually, this feature allows the system to display relevant data without prompting, and might improve situational awareness. However it also presents a weakness; when milestone data are not entered, the system does not advance. We have worked to overcome this weakness by adding a level of redundancy to the data milestone entry as some of the data may come from either the NPR or the automated anesthesia information system.

The ‘Case Setup’ pane (see Fig. 5) is the first dynamic pane to appear during a case, and is triggered by the departure of the previous patient from the OR. This pane augments the persistent panes with data pertaining to the upcoming patient’s previous surgical history, voiding and fasting status, postoperative disposition plans and the location of waiting family members. It also allows the OR team members to see provisional information about the contemplated procedure. As the patient’s identity (name, age, sex, and medical record number) and the procedure to be performed are confirmed by members of the perioperative team interviewing the patient, these are promoted from provisional to confirmed data on the display in the OR. This is done via a web-page interface by a perioperative team member outside the OR,[3] and the corresponding fields on the display in the OR change from gray to white as the data are confirmed. For example, in Fig. 5, the patient’s identity has been confirmed, but the contemplated procedure is still shown as provisional information. The web interface allows team members outside the OR to append details for consumption by the OR team. For example, in Fig. 5, an associated diagnosis (renal failure), dialysis status and details about potential allergies have been added in the ‘patient care notes’ pane.

Other just-in-time information that is either confirmed or recorded and displayed for the OR team can be seen in Fig. 5. Additionally, the ‘Case Setup’ display alerts team members about the presence of unique information that is too complex to capture on the display. For example, the capital ‘P’ associated with the medical record number (obscured in the illustration) indicates that the patient requires some type of isolation precautions, alerting the care team to investigate the detailed medical record for specific information. This data element appears in the persistent pane area and stays visible throughput the case.

The next dynamic pane is the ‘Time Out’ pane (Fig. 6), whose appearance is triggered when the patient enters the OR. The ‘Time Out’ pane again provides case verification to reinforce data elements as patient identity, procedure and laterality. The ‘Time Out’ pane is displayed at the beginning of the case, so physiologic trend data are displayed so that the team can all see baseline values. There is also a reproduction of our institution’s standard checklist for the timeout procedure. This is displayed to facilitate joint review of the checklist by the collected OR team, prior to incision.

The ‘Intraoperative’ pane (Fig. 7) appears when the patient is ready for surgical prep. It augments the persistent panes with real-time physiologic monitoring, as well as trend data for the previous hour and detailed data over the last four minutes. Note that in Fig. 7, data from surgical instruments that can affect physiologic variables (e.g., laparoscopic insufflation pressure) are displayed on the same temporal axis as the vital signs trends. Additional information such as estimated blood loss and urine output can be presented graphically and numerically along with time stamps to provide an estimate of data staleness.

In practice, the tabbed panes reliably advance as the case progresses, presenting contextually appropriate information as it is needed throughout the case. The panes advance as long as OR personnel contemporaneously complete the routine tasks that trigger the advancing function, and thus no additional effort is required.

Taken together, our results to date do not negate our second hypothesis, namely, that the available data would be sufficient to create a single, large-format display automatically integrating and displaying high-level team-synchronizing data about the patient. Furthermore, our third hypothesis that automatically or clinically generated signals could keep the

[3] This web interface was developed as part of a proof of concept demonstration. The integration system is intended to take in such data automatically as they are entered into an electronic health record by preoperative personnel. However, our institution does not currently use an electronic health record for preoperative documentation.

display synchronized with the state of the surgical procedure is also not negated.

Discussion

The immediate objective of the project was to develop and implement a prototype system to perform integration and display of information from a variety of disparate sources, including hospital information systems, patient monitors, surgical equipment and a location tracking system. We also succeeded in creating a display upon which selected synchronizing data are integrated and displayed in real time with an 'always-live' image viewable from any place in the OR, and which automatically updates without any interaction by OR team members.

As described in 'Results' section, hardware limitations are not a factor in our current installation and network. On the other hand, the requirement to create custom interfaces for each new device and information service to be integrated is a challenge that could limit wider adoption of the system. However, we anticipate that this issue will diminish as a library of interfaces is created to support successive installations.

In contrast to the hardware aspect, presenting the vast amount of information from hospital information systems, anesthesia and surgical systems, surgical equipment, and workflow support systems in a usable and cohesive way on a single, wall-mounted display is a challenge. The information must be rich, complete and accurate to be useful. It must also be visible and legible anywhere in the operating room, which for a 60 m^2 OR can be up to eight meters away. These are counterbalancing requirements: richness calling for more data vs. legibility calling for larger fonts (and hence, fewer data). We attempted to meet the display challenge by two approaches. First, we effectively expanded the size of the display by adopting a tabbed dynamic scheme for some of the contextually relevant data, and we made the tabbing process automatic by linking it to milestones recorded in clinical information systems as part of the regular OR workflow. Next, we involved the eventual users directly in the selection of data for display, applying three simple rules: [1] the data had to be available from a machine readable source; [2] the data had to be available to the system with no requirement for user interaction; [3] and the data had to be of interest to two of the three major parties in the OR in order to safety and efficiently provide patient care.

We are currently investigating other information that would be deemed sufficiently important in the high level orientation of team members to warrant inclusion on the display, such as laboratory values, current orders and medication lists, and co-morbid conditions. Each of these is available as an XML service from our HIS, but this is not the case in all environments. Deploying the software in other environments involves knowledge of any new devices or system interfaces; the IT or networking systems required; and any operational preferences of the users.

The absence of digital data presents the largest single limitation of our system. For example, while most physiologic monitors and electronic surgical devices do provide digital outputs, some still do not. Also, many ORs still lack computerized systems for clinical and workflow documentation, and anesthesia information management systems still have not achieved widespread adoption. Our system would be of little utility in a 'digitally sparse' environment, simply because there would be no source of data to integrate or display. Lack of standards for communication between devices is also a limitation. At present, each new device to be integrated requires investigation of its communication protocol, and in some instances the creation of a custom interface.

On the other hand, we believe that there will be increasing pressure to provide digital access to device data so that they may be used for the benefit of the patient. For example, 'decision support' presents fertile ground for utilizing the summation of operative and perioperative data to provide additional information concerning the patient. Utilizing physiologic information, it has been shown that decision support applications can be augmented through expert systems that help create and validate alarms based on physiologic parameters. The integration of information from several sources improves reliability of alarms, decreases false alarms, has fewer missed alarms, and creates alarms that are more clinically acceptable [18–20]. This provides a basis for utilizing integrated medical data to provide clinically relevant 'smart' alarms during the perioperative process for decision support and augmented vigilance in the operative environment.

Ongoing development of the system is taking place with the objectives of conforming to existing standards efforts and encouraging developing protocols for supporting the coordination and sharing of information in the operating room. A version of the system participated in the Patient Care Device domain of the 2006 IHE Connectathon, performing the role of a Device Observation Consumer and presenting data from multiple physiological monitors. We also hope to utilize the DICOM surgical workflows for image guided surgery, as they are developed, to help coordinate the interaction between the integrated display of team-synchronized data and the related imaging workflows.

Looking ahead, we believe that part of the overall benefit of the system will be the creation of new high-value information through the integration and processing of OR clinical and administrative data. By integrating with the hospital patient record, OR scheduling information, and patient location information obtained through the indoor positioning system, completely automatic process monitoring and exception detection functions will be enabled in the perioperative environment. As a proof-of-concept, we have demonstrated fully automatic detection and notification of wrong patient/wrong location errors [15]. More fundamental applications of this concept include sending automatic alerts to provide necessary surgical equipment to ORs about to start cases for which the needed devices are missing.

These forms of decision support need not be purely geographically based. For example, Xiao et al. [21], have demonstrated the use of vital signs data flowing from networked monitors to help establish the patient in- and out-time for real-time operating room management. Extending this concept, fusion of data from real-time location tracking systems, event marks from an anesthesia information system, and the OR scheduling system would allow intelligent PACU bed allocation. Such systems would probably be welcomed by OR managers responsible for coordinating care in OR suites. The bulk of communication in operating room suites revolves around task coordination, managing equipment, preparing the patient for surgery, staffing, room assignments, and scheduling. Each of these activities engender specific communication tasks, some of which are brief enough to be accomplished by short messages sent to devices, or by status displays [11].

Other opportunities to utilize the integrated data to provide new information are being investigated. For example, automated systems can reverse the direction of effort required to move a patient from the PACU to a post-surgical bed [22]. Decision support systems can also help clinicians reduce the incidence of documentation errors that prevent billing for services if uncorrected, thus establishing a simple financial justification for investing in such systems [23].

The objective of this study was to determine whether standard personal computers and available software could be used to substantially integrate the digital data available from the various devices and information systems present in the OR. Our results indicate that such integration is indeed readily feasible, limited only by the availability of machine-readable data sources and the size and resolution of available displays. Additional interfaces and data sources are being investigated to extend the system beyond the operating room and ultimately, to provide a complete picture of the patient throughout the entire perioperative process. Our long-term objective is to provide decision support, augmented vigilance, and workflow support, increasing both efficiency and safety in the perioperative environment by utilization of information that was previously unobtainable.

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References

1. Sandberg WS, Daily B, Egan M, Stahl JE, Goldman JM, Wiklund RA, Rattner D (2005) Deliberate perioperative systems design improves operating room throughput. Anesthesiology 103:406–418
2. Hanss R, Buttgereit B, Tonner PH, Bein B, Schleppers A, Steinfath M, Scholz J, Bauer M (2005) Overlapping induction of anesthesia: an analysis of benefits and costs. Anesthesiology 103:391–400
3. Torkki PM, Marjamaa RA, Torkki MI, Kallio PE, Kirvela OA (2005) Use of anesthesia induction rooms can increase the number of urgent orthopedic cases completed within 7 hours. Anesthesiology 103:401–405
4. Cendan JC, Good M (2006) Interdisciplinary work flow assessment and redesign decreases operating room turnover time and allows for additional caseload. Arch Surg 141:65–69; discussion 70
5. Friedman DM, Sokal SM, Chang Y, Berger DL (2006) Increasing operating room efficiency through parallel processing. Ann Surg 243:10–14
6. Harders M, Malangoni MA, Weight S, Sidhu T (2006) Improving operating room efficiency through process redesign. Surgery 140:509–516
7. Sokolovic E, Biro P, Wyss P, Werthemann C, Haller U, Spahn D, Szucs T (2002) Impact of the reduction of anaesthesia turnover time on operating room efficiency. Eur J Anaesthesiol 19:560–563
8. Guerlain S, Adams RB, Turrentine FB, Shin T, Guo H, Collins SR, Calland JF (2005) Assessing team performance in the operating room: development and use of a "black-box" recorder and other tools for the intraoperative environment. J Am Coll Surg 200: 29–37
9. Healey AN, Sevdalis N, Vincent CA (2006) Measuring intra-operative interference from distraction and interruption observed in the operating theatre. Ergonomics 49:589–604
10. Lingard L, Espin S, Whyte S, Regehr G, Baker GR, Reznick R, Bohnen J, Orser B, Doran D, Grober E (2004) Communication failures in the operating room: an observational classification of recurrent types and effects. Qual Saf Health Care 13:330–334
11. Moss J, Xiao Y (2004) Improving operating room coordination: communication pattern assessment. J Nurs Adm 34:93–100
12. Ren Y, Kiesler S, Fussell S, Scupelli P (2007) Trajectories. In: Multiple group coordination: field study of hospital operating suites 40th Hawaii international conference on system sciences. Honolulu, HI
13. Sandberg WS, Ganous TJ, Steiner C (2003) Setting a research agenda for perioperative systems design. Semin Laparosc Surg 10:57–70
14. Marvik R, Lango T, Yavuz Y (2004) An experimental operating room project for advanced laparoscopic surgery. Semin Laparosc Surg 11:211–216
15. Sandberg WS, Hakkinen M, Egan M, Curran PK, Fairbrother P, Choquette K, Daily B, Sarkka JP, Rattner D (2005) Automatic detection and notification of "wrong patient-wrong location" errors in the operating room. Surg Innov 12:253–260
16. Marjamaa RA, Torkki PM, Torkki MI, Kirvela OA (2006) Time accuracy of a radio frequency identification patient tracking system for recording operating room timestamps. Anesth Analg 102:1183–1186
17. Dain S (2002) Normal accidents: human error and medical equipment design. Heart Surg Forum 5:254–257

18. Krol M, Reich DL (2000) Development of a decision support system to assist anesthesiologists in operating room. J Med Syst 24:141–146
19. Navabi MJ, Watt RC, Hameroff ST, Mylrea KC (1991) Integrated monitoring can detect critical events and improve alarm accuracy. J Clin Eng 16:295–306
20. Oberli C, Urzua J, Saez C, Guarini M, Ciprianio A, Garayar B, Lema G, Canessa R, Sacco C, Irarrazaval M (1999) An expert system for monitor alarm integration. J Clin Monit Comput 15: 29–35
21. Xiao Y, Hu P, Hu H, Ho D, Dexter F, Mackenzie CF, Seagull FJ, Dutton RP (2005) An algorithm for processing vital sign monitoring data to remotely identify operating room occupancy in real-time. Anesth Analg 101:823–829, table of contents
22. Meyer MA, Sokal SM, Sandberg W, Chang Y, Daily B, Berger DL (2006) INCOMING!—A Web Tracking Application for PACU and post-surgical patients. J Surg Res 132:153–158
23. Spring SF, Sandberg WS, Anupama S, Walsh JL, Driscoll WD, Raines DE (2007) Automated documentation error detection and notification improves anesthesia billing performance. Anesthesiology 106:157–163