Pillars of a Smart, Safe Operating Room

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Abstract

Major gains in patient safety can be achieved through development of innovative approaches to the care of surgical patients. Investigators and clinicians have conceived an “operating room of the future” (ORF) that epitomizes those current and future enhancements that can contribute to patient safety in the operative environment. In this article, we explore these enhancements in the context of their development as University of Maryland (UM) ORF initiatives. We discuss the four “pillars” of our research that affect patient safety: (1) surgical simulation, (2) “smart image,” (3) informatics, and (4) ergonomics/human factors. In surgical simulation, in addition to virtual reality and physical trainers of surgical skills, we are developing a cognitive simulator for teaching clinical decisionmaking in a manner that emulates the actual surgical and clinical experience. Smart image uses computer-enhanced imaging to provide safe rehearsal before surgery and image-based guidance during operations. Informatics analyzes and improves the processes within the perioperative environment, including accurate identification of the patient, care providers, and tools; establishment of clear communication among the surgical team members; and provision of real-time, graphically presented feedback. Ergonomics and human factors are used to design physical and informational workplaces for better outcomes, both for patients and care providers. Research in regard to these pillars shows the promise of an ORF as a vital component of a pervasive patient safety environment.

Introduction

Almost two decades ago, Sir Alfred Cuschieri, one of the true pioneers of minimally invasive surgery (MIS) and the operating room of the future (ORF), asserted that laparoscopic surgery represented “a rare instance in surgical history where an advance in patient safety and surgical technique has been so rapid and so profound.”[1] Today these words continue to ring true and bring inspiration to those who seek to move beyond laparoscopy, to probe, discover, and invent the ORF in anticipation of the patient benefits that will follow. Surgeons and researchers at the University of Maryland (UM) have contributed significantly to the growth and evolution of laparoscopic surgery and to the development of the concept of the ORF.

The state of the art in operating room (OR) safety, while always evolving, can be revolutionized through smart application of technology and knowledge. Recent advances in technology have moved us from a traditional surgical suite toward one that is more efficient and safe. That evolution continues in the ORF, where research seeks to identify and address novel approaches to an array of domains often overlooked in the safety literature. While the ORF has been embraced by many institutions in unique ways, the advantages of a number of promising approaches to safety can be exemplified through the UM ORF initiative. Our approach has been to identify strategic areas for which solutions to problems would be significant, even disruptive, in the advancement of the concept of ORF. Of the many fields of investigation to be pursued under the rubric of ORF, we have focused on four key areas. Broadly titled, these focus areas are (1) cognitive simulation, (2) informatics, (3) “smart image,” and (4) ergonomics/human factors. Considerable overlap is found among these complementary research fields. In this article, we describe the aim of each of these four pillars and the work that we are doing within each pillar to improve patient safety. We conclude each section with an idealized view of what the future may hold.

Cognitive Simulation

As new surgical technologies and techniques emerge, patients are often torn between wanting to avail themselves of the latest therapeutic options, yet wanting to be reassured that their surgeon is adequately trained and has already ascended the requisite learning curve. Surgical educators have been hesitant to mandate simulators for the training of surgical novices even as they recognize the need to separate surgical trainee learning from direct patient contact. The cautious approach to acceptance of simulation training was based, in part, on the initial lack of robust scientific evidence to support the use of medical simulation for skills training and also on the lack of knowledge of how to effectively apply simulation to a surgical skills training program. Fortunately, the acceptance of simulation training by boards and certifying agencies is on the rise.[2]

Simulation represents a valuable alternative to using patients as hands-on training material for care providers. It improves patient safety by moving the learning phase away from patients.[2, 3] Typically, simulations allow the practice of manual skills or procedural steps involved in a discrete medical event or team-based activities, such as a trauma admission, airway management, or surgical crisis.[4] Simulation practice has steadily gained credence as a method of improving knowledge and performance. Additionally, the use of simulation for credentialing and assessment of competencies is acquiring acceptance as a means of improving patient safety.[5]

Many patient safety issues arise not out of poor manual and procedural skills, but rather from lapses in clinical judgment leading to adverse events (AEs). Simulation can provide time-effective experience and training to residents on restricted work-hour schedules. In particular, cognitive simulation can provide clinicians with the opportunity to rehearse and explore the process of diagnosis and treatment.

Given the effect the development of a cognitive simulator can make in regard to training and patient safety, the UM ORF simulation team has created a “Maryland Virtual Patient” (MVP) prototype. This multivariate cognitive simulation possesses the ability to grow, change, and experience biologic functions, to allow trainees to experience realistic interactions with a simulated patient. The UM ORF has developed this working prototype as an automated tutor for medical students. It currently functions as a clinically accurate and computationally tractable model of human physiology, both normal and pathological, that emulates some six to eight gastrointestinal diseases at levels of detail sufficient for the needs of training medical students. A broader range of disease models is being developed.

The MVP automatically undergoes physiologic processes over time and can communicate its symptoms to trainees, which makes it a combination of an intelligent cognitive agent capable of understanding, reasoning, and responding in English and a physiologic agent—i.e., a patient with a disease. With the MVP, just as with an actual patient, the trainee can practice communicating, ordering tests, prescribing treatments, and observing treatment results. The MVP includes a language recognition and text generation component to generate relevant statements: the MVP can understand the user's questions and statements and also decide what to communicate back to the student. This decisionmaking process is akin to the reasoning process guiding the "life" of this physiologic agent.

Significant to this MVP project is the use of artificial intelligence so that learners can interact with the simulation using natural language. This dynamic represents a considerable advance over other simulations, which depend on a prescribed "script" of events or preset branching points in a scenario. The MVP can be given a variety of treatments at any time and in any doses, appropriately or inappropriately, and it responds as a typical patient. The potential benefits of using the type of dynamic simulation represented by the MVP are improved clinical decisionmaking, provision of realistic experiences for training clinicians, and the provision of well-trained care providers for patients.

Simulation is gaining wider acceptance for credentialing procedural skills, supplying criteria-based certification of safety-critical skills, and providing opportunities to improve clinical judgment through the practice of cognitive skills. It is expected that future clinicians will gain experience during training less on animals, cadavers, and real patients and more on realistic simulations of clinical experiences. Because simulation faithfully reproduces a variety of clinical challenges, the likelihood increases that a surgeon will have familiarity with a multiplicity of patient-specific problems.

Smart Imaging

Medical practice is considered among the most complex and difficult fields. That no two patients are exactly alike is one of the challenges that makes it so. Anatomic and physiologic differences make each case unique. In surgery, these variations can complicate an operation; the discovery of unexpected anatomical variations often requires a surgeon to stray from standard, well-practiced techniques to attempt a novel approach to the procedure. With novelty comes a reduced margin of safety. This situation is exacerbated by a trend toward further physical separation between the patient and interventionalists (e.g., surgeons, endoscopists, radiologists) and a greater dependence on an image of the patient's (target) anatomy to effect therapy or establish a diagnosis.

Recently, a number of innovative approaches to enhance the scope and precision of image-guided surgical procedures have been under development. These include augmented reality images used to guide laparoscopic procedures;[6, 7] advanced image-guided navigation; haptic (touch-based) feedback; telesurgical capabilities used in robot-assisted procedures;[8] and even subject-specific anatomical models developed for minimally invasive cardiac surgery.[9] These approaches have the potential to bring in a new level of sophistication and accuracy to image-guided surgical procedures. Our focus has been on developing a "smart image" to guide the interventionalists.

“Smart image,” as we have defined it, refers either to the process of extracting elements from an environment and imparting them to an image or to acquiring elements from within a scene and enhancing them. The result in either case is a more meaningful visualization of the operative field. Although many applications exist within this definition, Maryland’s smart image team is working toward performing the first laparoscopic surgery guided completely by smart image.

Typically in laparoscopic procedures, diagnostic imaging—including x-rays, computerized tomography (CT), and magnetic resonance imaging (MRI) scans—can provide a preview of patient physiology. Often, however, these diagnostic images are in a static format that does not allow the care provider to interact meaningfully with the information the images contain. Current advances in smart imaging can be used to improve patient safety by providing the caregiver with a more interactive experience. A set of two-dimensional (2D) slices of a CT scan can be transformed into a three-dimensional (3D) computer model so that surgeons can preview a realistic view of the patient’s anatomy before an operation. This type of smart imaging provides an interactive “fly-through” view that allows the surgeon to explore the anatomy in detail.

With advances in computing power, these previews could be mapped more realistically to interactive simulators that would permit rehearsal of a surgical procedure that might include attempts at novel approaches before surgery begins. During real surgery, these smart diagnostic images could be integrated into the surgeon’s actual view of the patient.

At the Maryland ORF project, we are working toward matching the minimally invasive surgeon’s video view of the surgery with computer-generated models from diagnostic imaging.[10] Such imaging could provide the surgeon with real-time “x-ray vision” during the operation. Thus, the underlying structure, such as the position of a tumor beneath the surface of a larger anatomic structure or blood vessels within the liver, could be seen. Vessels could be contrast-enhanced in a single, high-resolution CT scan before the surgery. Then, during surgery, low-dose/low-resolution CT scans could be used to transform the high-resolution CT image to match the movement of the patient’s anatomy during surgery.[11, 12] This would allow intraoperative visualization of anatomy that retains the enhanced contrast vessels, a unique ability that is not possible at present.

CT scans can provide enhanced intraoperative visualization of deep structures far superior to that of laparoscopes. However, the use of continuous CT exposes the patient and surgeon to a radiation level that remains a concern. Therefore, a major thrust of our work is to design, develop, and test several dose-reduction strategies and to incorporate these into our proposed continuous CT-guided surgical navigation system.[11, 13] Our preliminary work suggests that our strategies would allow us to lower the net radiation exposure to the patient to levels commonly viewed as acceptable in cardiac catheterization and interventional radiology procedures. In the long term, we also propose using telemanipulators to remove surgeons from the CT room and thereby shield them entirely from radiation exposure while they are performing the procedure.

In the future, we expect that advances in computing power will lead to a routine interactive review of patient anatomy through 3D modeling. Rehearsal of surgery on a detailed computer model of a specific patient would allow a surgeon to work out potential complications through simulated surgery before the actual operation. During surgery, surgeons would have the ability to see diagnostic images projected onto or viewed next to a patient's actual physiology to provide a synthetic-vision view of the patient's anatomy integrated with additional diagnostic information.

Informatics

The manager of a well run OR suite should maintain an awareness of the surgeons, anesthetists, nurses, patients, and major pieces of equipment that are present. The harsh reality in current medical practice is that most commercial warehouses and supermarkets track their assets and inventories in a far more sophisticated way than we do in the perioperative environment. Wal-Mart closely tracks the location of its 99-cent paper towel inventory, but a charge nurse in a typical operating suite might have to search for a C-arm or ultrasound machine.

Well executed process management is a key to excellence in health care. Inefficiency, redundancy, communication problems, usage problems, and system failures are among the issues driving annual health care expenditures to over a half-trillion dollars, or the equivalent of 30 to 40 cents of every health care dollar.[14] The challenge to the health care industry is to understand and improve processes that lead to system failures and lower efficiencies, while simultaneously minimizing risks to patients and caregivers. This challenge must be met in order to offset the growing fiscal demands placed on the health care enterprise. Fiscal, operational, regulatory, and patient safety demands that occur within the constraints of limited resources increase the complexity of both performing a single procedure and of coordinating multiple procedures. A need exists to create a system that can objectively evaluate the efficacy of the many processes that occur in any OR as they relate to time, cost, and patient outcome.

Informatics—the science of collecting, classifying, processing, retrieving, and disseminating data—can be a key to patient safety. Using information technology to improve patient safety has been a hallmark of recent patient safety efforts. These efforts have ranged from the use of barcode IDs for patients to the application of computerized physician order entry systems. Computer systems provide an infrastructure in which patient safety efforts can be implemented through novel uses of information. Process improvement—specifically the identification, evaluation, and quantification of perioperative processes—is the focus of UM ORF informatics research. By studying perioperative workflow at the UM ORF, we hope to track, model, and ultimately better integrate existing and emerging OR technologies in a manner that contributes to patient safety, OR efficiency, and process improvement.

We anticipate that information technology and location-aware tracking technologies will have a valuable and indelible influence on health care, one that results in ensuring that patients receive a care experience characterized by a safe and healing journey through the health care system. Currently, no accepted measure of efficiency exists within the OR environment. There is no quality matrix or framework to evaluate operational processes to determine the level of operational performance. We do not have a means to show the patterns of our efficiencies or failures. We plan to apply a novel approach that integrates technologic components and corporate and manufacturing methodologies, so that system failures are minimized or eliminated, and investment returns are maximized.

Within the informatics pillar, the UM ORF research program is developing three specific applications to improve patient safety. These are smart environments, operational glitch analysis, and group-based communication technology. All three are potential application areas of informatics technology that hold promise for improving perioperative safety and efficiency.

Smart Environments

In pursuit of this future environment in which patient safety is ever increased and clinician education is ever more successfully tailored, we have designed and implemented a prototype Context Aware Surgical Training (CAST) Environment as part of UM's Advanced Simulation, Training, Research, and Innovation (MASTRI) Center. The CAST goal is to create an intelligent pervasive computing environment that can enhance the training of surgical students, residents, and specialists. CAST research builds on prior work on context aware "smart spaces."[15, 16] It uses Web-based infrastructure and software applications in academic and professional development programs.[17] A cornerstone of this project is tracking student presence using technology as varied but common as radiofrequency identification (RFID) tags or even mobile phone or personal digital assistant (PDA) Bluetooth® signals, so that the smart environment "understands" the access and asset use of students.

Our pilot system integrates training resources available in the MASTRI Center into a context aware training environment that can recognize the presence of a trainee or mentor and take appropriate action based on known training goals and parameters.[18] The success of our CAST "smart environment" would lead to scaling it to meet the needs of an operative environment, where technologic demands are often analogous to those seen in the training environment.[19] Tracked blood product data could be compared to tracked patient data so that, for example, clinicians would be alerted immediately if incompatible blood products were brought into an OR. This type of approach to safety is the goal of advancing interactive information management, resource management, and content management via a seamless process.[16, 20]

CAST illustrates how potential safety and efficiency issues can be addressed and resolved when surgical training environments and the corollary activities in the ORF are transformed into a pervasive computing environment. In this environment, devices, simulation systems, software agents, and legacy computing components cooperate seamlessly to support the activities of doctors, nurses, other perioperative team members, medical students, and their mentors. A requirement of such an environment is that the constituent systems should be aware of, or have access to, a context model that represents relevant information on the devices, services, people, environmental conditions, tasks, and activities in the space.

Such environments entail many challenges in terms of developing hardware, system, software, and human-computer interfaces.[20] One such challenge is that the rapid development of new technologies, combined with iterative introduction of these technologies into the OR, creates a formidable barrier to achieving a well integrated operative information system.

In the future, smart environments would guide the training of medical care providers by tracking their progress, providing feedback, and assuring proper credentialing. Smart environments would also speed training and improve safety. In the operative environment, this same type of tracking would augment human vigilance, further preventing adverse outcomes through automated, context aware safety checks.

Operational Glitch Analysis

Crucial questions facing OR managers and hospital administrators are how to process and analyze the vast array of data being collected and how to use the data rapidly for effective decisionmaking in a large-scale coordinated environment, such as the OR. Building upon the results of smart environment data and models of perioperative workflow, it is possible to identify glitches in any system so as to improve both efficiency and patient safety. Data are often collected about work processes for the purpose of revealing systems vulnerabilities, inefficiencies, or "glitches" in general. Using data collected from the ORF workflow, we can, in real time, generate from that environment pertinent statistics from which we can identify sources of variation and communicate these variations to relevant stakeholders.

The UM Medical Center (UMMC) currently maintains an active glitch database that contains information from its 19-room surgical suite. Among the items reported are reasons for surgical case delays and issues regarding equipment and supplies. This database provides information that is used by senior management for accountability and by line managers for rapid process improvement.

A key to high reliability is reduced variations in the process of care.[21] Communication, performance feedback, and transparency are all cited as factors that can improve patient safety and create a culture of safety.[22, 23] In the UM ORF, we have implemented preliminary versions of a system capable of identifying variations in the management and scheduling of the suite of operating rooms. This prototype system includes a Web-based interface to the database that displays a graphic visualization of trends, provides for text-based search, contains automatically generated reports, and allows issue-centered exploration of historical data. Development of key concept graphs and trend presentations is achieved through conceptual modeling based on the patterns and the etiology of glitches. Information about both is considered vital for the determination of the information requirements necessary for rapid institutional learning and is derived from interviews with key stakeholders.

What is the future impact of operational glitch analysis on patient safety? Glitches and delays in the process of running an OR (or any other such venue for care) would be quickly identifiable by both OR managers and hospital administrators. The immediate availability of such information, the ability to instantaneously interact with that information to answer questions, and the data-driven decisionmaking that ensues, would enhance institutional learning. The ultimate hope is that by uncovering sources of variation and by treating the root causes, glitches can be eliminated.

Group-Based Communication Technologies

Miscommunication has been widely cited as contributing to adverse events in medicine. In the OR, AEs are more often related, not to technical competence, but to interpersonal aspects that are part of OR team functioning.[24, 25] Indeed, "insufficient communication" was the most frequently cited root cause of the nearly 3,000 sentinel events reported to the Joint Commission between 1995 and 2004;[26] not surprisingly, over 70 percent of all OR-related sentinel events between 1995 and 2005 cited communication as a root cause.

One approach to addressing communication problems has been through training in team communication and interpersonal communication skills and by formalizing communication procedures. Such strategies have been effectively employed in a number of arenas, including training in “crisis resource management” (CRM),[27, 28] establishing preoperative “time outs,”[29] and structuring work in intensive care units.[30, 31] While not a replacement for interpersonal improvements in communication skills, communication might also be enhanced through the smart application of technology.

We are currently examining the ability of technology to facilitate one specific aspect of the communications process: How changes to the surgical schedule can be communicated to the necessary parties through a timely and secure method. Such communication is necessary to ensure OR efficiency and patient safety. Many forms of communications are used to convey critical location, scheduling, and patient information to the perioperative team. These communications traditionally have taken place across and through an amalgamation of phones, pagers, computer scheduling systems, printed schedules, and face-to-face communications. Quality of care and safety are influenced directly by this jumble of communications, which often proves inadequate in terms of providing individuals and teams with the real-time knowledge required for high-quality decision support. Additionally, poor management of both the reallocation and replenishment processes in the OR can ultimately lead to interventions that are unsafe for patients.[32] Recognizing communication as a significant part of the management process, we contend that flow or process breakdowns that occur in the perioperative environment are often preceded by a variety of communication breakdowns and have collateral repercussions.

Technology can be used to communicate action plans in a concise, up-to-date format to all team members. Technology can facilitate propagation of an initial action plan or alert a team to last minute plan changes. Deployed properly, technology could reduce the time and effort required to coordinate the running of an OR suite safely. Bearing such concepts in mind, we are working to bridge key gaps between information systems and care providers so that the people who need accurate information have timely and ubiquitous access to scheduling and operative plans and to equipment status. Digital solutions can be deployed that will both assist in the communication of operative plans and facilitate acquisition of communications data that can serve as source data, permitting analysis of the communications that occur in the OR. Rapid, automated distribution of accurate, necessary information to all team members can be achieved through a coordinated combination of smart technologies, including the Internet, pagers, and voice-based (phone) applications.

Group-based communication technologies hold great promise for improving patient safety. The multiple OR surgical suite, which often experiences schedule disruptions, would be kept running smoothly as all the team members would be apprised at all times of the plan of action that is the most current. Handheld computers, pagers, and wireless phones would be linked into a centralized Web-accessible schedule and operative plan that all members could access and, if needed, update. Changes will be “pushed” to the relevant team members though automated paging and phone calls, so that the proper equipment, people, and patients arrive in the right OR at the right time. With all team members knowing the plan, there would be fewer surgical complications, the result of team members being freed from solving logistic problems so they can focus on the operation at hand.

Ergonomics and Human Factors

Ergonomics and human factors are two related branches of study that examine the relationship between people and their work environment. Ergonomics often focuses on the physical environment and the human body, while human factors center more on the cognitive aspects of performance. The same ergonomics and human factors techniques credited with making industrial processes safer and more efficient can be applied to the analysis and improvement of OR operations. Tools, such as video analysis and motion tracking, can be used to analyze current practices, identify inefficiencies and dangers, develop solutions, and measure improvement. "Best practices" to maximize safety and efficiency can be developed based on empirical data.

Our discussion of workflow to this point has taken a macro or panoramic view; for example, how might we most effectively track and bring together the people and assets necessary to ensure that a patient's surgical experience is safe and efficient. Through human factors and ergonomics, we have the ability to focus on a more micro-level analysis, such as how the physical interface between the surgeon and the patient could be improved and the associated work space chaos and stressors of MIS be reduced.

The patient is the center of the ORF.[33] During MIS, the interfaces between the patient and the surgeon are critical to both the safety and quality of patient care and surgeon welfare. Patient-surgeon interfaces are complicated by compromises in equipment design, technology limitations, operating theatre layout, and technical approaches.[34, 35] In particular, ergonomic problems in the MIS workspace, such as obstructing catheters and cluttering tubes, can elevate the chance for contamination, increase surgical risks to the patient, and reduce work efficiency.[36] Optimal workflow during MIS stands to be achieved through better understanding of patient-surgeon interfaces, both intracorporeal and extracorporeal. In the ORF, advanced technology could function as a key enabler, allowing an optimal patient-surgeon interface.

Some of our current work is focused on establishing quantitative, valid measures of workflow within patient-surgeon interfaces, identifying ergonomic problems that result as a consequence of workplace designs (e.g., arrangement or management of cables and catheters), and demonstrating key barriers to optimal workflow that present direct safety and efficiency concerns. One project is based on a collaboration between surgical experts and human factors experts.[35] Previous experiences in video capturing[37] and analysis[38] are being used as a basis for development of workflow measures and identification of ergonomic inadequacies. Time-motion studies[39] have been conducted to collect objective data on activities in the patient-surgeon interface. Conceptual workplace layout designs are being developed, based on objective data and simulations of what workflow might be if interfaces were optimized.[40]

In the future, OR workspace layout would be optimized through ergonomic data and human factors analysis, and this optimization would lead to the establishment of "best practices" for an array of surgical operations. Proper layout would reduce risks of infection, speed operations, and reduce fatigue of surgeons and staff, all elements that could contribute to a reduction in AEs and improved patient safety.

Future Vision of the Operating Room Environment

Well-trained care providers, who have reached a level of proficiency on realistically simulated patients, are supported by an array of smart technology enabling surgical procedures to be performed in an ever safer environment. Cases start on time with all team members informed of the goals and possible trouble spots of each operation. Contingency plans are in place for dealing with anticipated complications. The smart environment checks that all required equipment and people are present and cross-checks drugs and blood products brought into the room, ensuring patient compatibility in terms of allergies and blood type. Surgeons do not have to fight fatigue and discomfort during surgery, as the layout of the surgical workspace is ergonomically correct. Thus, the time and effort needed to perform surgery is minimized and improvement of both technique and outcomes is realized.

Data from all aspects of the surgical procedure are collected in real time and combined with data from other processes to help identify safety and efficiency trends. These data are available to all stakeholders and are presented in interactive, graphic formats that aid in tactical and strategic decisionmaking for improved operations. Systemwide problems can be identified and root causes discovered. The transparent nature of both the data collected and the subsequent analysis of the data supports a culture of safety and encourages a systems-based approach to understanding AEs.

Conclusion

This utopian vision of the perioperative environment just described may sound unattainable, but prototype components of just such futuristic systems currently exist in some form. Significant time, effort, and advances in technology are certainly required before such a pervasive, seamless system can be implemented. However, achieving incremental advances is already possible through implementation of any of the systems or approaches described in this article. Additionally, technology, while certainly not a panacea for patient safety, might well serve to facilitate or augment a culture of safe medical practices.

Future surgical care will be safer and more efficient due, in great part, to simulation training for practitioners. Simulation represents a viable alternative to using patients as hands-on training material for care providers. As discussed, the future will see an increase in the adoption of physical simulation for credentialing procedural skills and for awarding certification of safety critical skills, in addition to the regular use of cognitive simulation to improve clinical judgment. However, this rosy picture is tempered by the need for increased realism of simulators, for the incorporation of automatic assessment into training program modules, and for studies that demonstrate the validity and effectiveness of procedural simulation training.

While many image-guided therapies are already enhancing patient safety and therapeutic efficacy, substantial work must be done to accelerate development of image capture, processing, and display. A strong desire exists on the part of many surgeons to have the capability of rehearsing a procedure on a simulation of the specific patient before performing it. Rehearsal would entail the building of a precise model of the patient’s pathology by way of imaging and loading the model of the patient into a simulation system that realistically replicates the patient’s condition. The optimum outcome of this development is a surgeon’s “practicing” of a procedure on an exact model of the patient, then entering the OR and performing the surgery. Computer scientists and engineers have not yet incorporated advances in computing power to achieve the level of fidelity necessary to make such rehearsal practical.

Some of the most significant improvements in health care may evolve from refined information systems capable of reducing medical error, improving surgical efficiency, minimizing risks to patients and caregivers, and reducing costs. Yet, challenges still need to be overcome by those engaged in medical informatics. The current state of medical informatics is still one of fragmented information systems and a lack of comprehensive standards for information exchange between information systems. Initiatives are underway for a "universal electronic medical record,"[41] the implementation of which should facilitate progress toward resolving these challenges. However, even achievement of such an initiative can be viewed as only a first step toward using the power of informatics for comprehensive patient safety.

Technology itself can be a barrier to safety if improperly designed or implemented. Application of human factors and ergonomic principles can help ensure that technologies facilitate rather than impede safe practices. Applying human factors to information systems can ensure their usability. Similarly, ergonomics and human factors analysis can achieve proper configuration of the perioperative space to decrease risk of infection, speed operations, and reduce surgeon and staff fatigue, leading to a reduction in AEs and improved patient safety.

The concept of an ORF has, in fact, been embraced by many institutions. Implementing key aspects of ORF practices has already increased patient safety, although other aspects remain, which require much work before realization of tangible safety goals. Given the progress already achieved, the medical community should consider the ORF to be a key component within a broader context of a safety culture.

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