Commentary

Procedural Simulation: A Primer

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Procedural simulation will be a revolutionary change in how health care providers maintain their proficiency and skill. Visionary leaders are already examining how this educational technique will be integrated into traditional curricula, and interventional specialties will be at the leading edge of this revolution. The role must be defined that simulation will play, new educational models must be developed around it, and studies must be performed that will meet the demands of a skeptical profession. Only then will the first truly revolutionary change in medical learning have been achieved since the advent of animal experimentation nearly 1,000 years ago.

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Abbreviation: FDA = Food and Drug Administration

TRADITIONAL methods of medical education have not changed fundamentally in centuries. The time-honored use of older, more experienced "healers" to train younger apprentices is rooted in ancient Egyptian medical practice. Learning from animal dissection was first promulgated by Galen in the Middle Ages. The system used by most Western hospitals was outlined by Abraham Flexner and William Stuart Halsted in separate reports in the early 20th century. Flexner's 1905 report defined the modern structure of medical school education, whereas the concept of a residency was formalized by Halsted between 1904 and 1910 (1). The Halstedian model of medical education established step-wise, time-based postgraduate training, with patients serving as part of the teaching materials during prolonged periods in the hospital and residents assuming gradually greater independence and responsibility under faculty supervision as the trainee progressed through the years of apprenticeship.

Now, 100 years later, medical educators confront the most fundamental changes since Flexner and Halsted. Federal and private reimbursement plans have turned the basis for Halstedian education on its head. Hospital length of stay is shorter for every disease, there is a new emphasis on outpatient and minimally invasive therapies, patients who are in the hospital are more severely ill on average, procedures are more complex, and federally mandated restrictions now define the length of time a resident may be in-house.

What can we conclude from all of these changes? That our traditional system of medical education has outlived its usefulness. Consider that today we still pursue the same medical education model that worked so well when the most advanced technology in America was the Model T. Consider, too, that trainees today have little contact with patients and reduced procedural experience during residency. In some European countries, surgical residents enroll in operative fellowships after completion of residency simply to obtain ample surgical experience. The effect of the dwindling availability of highly experienced physicians will become apparent first in those countries where the most severe restrictions on patient contact hours have been enforced, in Europe before America, and in those systems that have rewarded efficient care by holding hospital stays as short as economically desirable. The results of these changes are not yet apparent in daily medical care but will become apparent over time.

When the first article describing an advanced vascular simulator was published (2), an accompanying editorial stated that "the methodology may well represent a breakthrough of astonishing and revolutionary importance." The point of this revolution was immediately understood by the editorialist: "virtual reality is not as good a teacher as the real thing, except that no one actually suffers" (3). Medicine's challenge is to examine the certain role that simulation will play in our future: medicine faces a crisis of education that is not entirely of its own making, but which it has not yet recognized fully and not yet addressed even minimally. We must decide now how to train the next generation of specialists so that a gap in expertise does not produce an unintended and unfortunate consequence of modern medical education: increased medical errors and decreased patient safety.

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HISTORY

In 1929, Edward Link invented the first flight simulator (**Fig 1**). With this device, for the first time, one instructor could observe the performance of multiple pilot trainees simultaneously, watching to see if any of them were performing simulated flight control inputs incorrectly. However, in a timeline foretelling simulation's adoption in medicine, only six units were sold over the first 5 years to the early adopters, the Army Air Force's mail carriers, who had experienced high pilot death rates because of bad weather on mail routes. Flight simulation's major breakthrough occurred during World War II, when the Army Air Force was experiencing high pilot death rates during nighttime carrier landings and needed a training system to reduce pilot errors and improve safety. After the introduction of a course teaching simulated nighttime carrier landings on Link's crude and simple "Blue Box," pilot deaths decreased by 90%. Today, commercial aviation is the leading user of simulation, with simulator-based flight training from the time of a new aircraft's introduction and through line training to maintain competence (**Fig 2**).

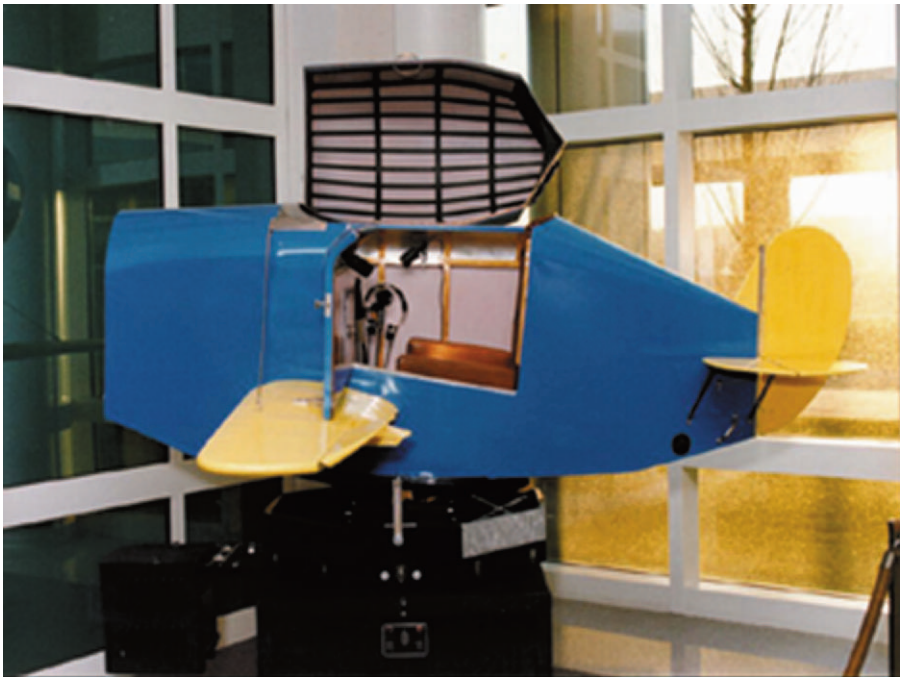

Figure 1. Edward Link's Blue Box, the first flight simulator, circa 1929 (photograph courtesy CAE).

Figure 2. Today's most advanced full-motion civilian flight simulator, the Airbus A-380, created by CAE (photograph courtesy CAE).

This history in aviation was not driven by the airlines, which incur large financial burdens for this expensive safety program, but rather by federal mandates that are designed to maintain a safe flying environment. Modern flight simulation pursues a multitiered approach in which full-motion flight simulation is reserved for specific training needs and occasional recertification or pilot examination. Early learning occurs in cheaper, lower-fidelity systems that allow rehearsal of many aspects of flight in static platforms that are easily configured to accommodate different cockpit arrangements and avionics displays. The parallels to medicine in each of these examples are striking, and for reasons of time and economy, it is likely that the full integration of simulation in medicine will result in a similar tiered approach to learning.

Satava has said that flight simulation did not make flying safer for the pilots; it made it safer for the passengers (R. Satava, personal communication, May 2004). An exact analogy can be made for medicine: medical simulation will not make medicine safer for doctors; it will make medicine safer for patients.

Properly implemented simulation can become a potent force to improve patient safety, as noted by the 1999 Institute of Medicine report, "To Err is Human" (4). The essence of simulation as a learning device is that errors can occur without consequence to patients. In a simulator, mistakes have no consequence other than to serve as markers of achievement: as a physician or other medical caregiver learns a procedure, errors should diminish and skill should improve. A properly

designed simulator can keep track of performance and present a record of learning to the user as well as to any designated authority, such as a program director or national Board, with use of mutually agreed-upon secure data transmission protocols.

Procedural simulators are of interest to those subspecialists who render patient care with use of minimally invasive techniques, such as interventional radiologists, neuroradiologists, and cardiologists who perform catheterization procedures; gastroenterologists and pulmonologists who perform endoscopic procedures; and surgeons of many specialties who perform minimal-access surgery. With simulators, the specialist learns unfamiliar techniques or procedures with a highly sophisticated integration of computers and interface devices that enable the user to interact with the on-screen display. Simulators are well-suited for rehearsing elements of a procedure that may be unfamiliar or infrequently performed. For physicians who have completed training, a simulator can be used to learn new procedures before practicing on humans. The most eloquently simple statement of simulation's role in medicine is that "simulation is to medicine what the microscope was to science: it lets us see and do what we could not see or do before" (N. Oriol, personal communication, December 2003).

DEFINITIONS

Medical simulation is the creation of an educational environment in which learning occurs through the use of a device, mannequin, or team, without the presence of an actual patient. Medical simulation is not just for physicians. It can be used across the entire spectrum of caregivers, from first responders through established physicians undergoing maintenance of certification training or examination. The simulation environment may include a full patient mannequin or a computer-based procedural simulator. Mannequin-based simulation is familiar to us from Basic Life Support or Advanced Cardiac Life Support courses in which simple mannequins are used for civilian-preparedness training. At the opposite end of the continuum, fully responsive anesthesia mannequins are capable of inhaling and exhaling anesthetic gases and responding in highly accurate ways to inputs from an instructor during training scenarios. It is sometimes called "realistic patient simulation" and has been well-described (5). It will not be considered further in this publication.

A simulator is a physical object that reproduces, to a greater or lesser degree of realism, a medical procedure that must be learned, and that incorporates a system of metrics that allows progress and learning to be recorded. These metrics are based on a curriculum of desired educational objectives for the training episode. In the best examples, these curricula are created first and the simulators are then designed to effectively measure learning through simulation. Simulators can look like mannequins, computer-based systems, or hybrid systems that combine a physical form and a computer interface. For the purposes of this article, we will not discuss other computer-based interactive multimedia systems such as CDs, which fall outside the purview of commonly accepted definitions of medical simulation. Therefore, a simulator is a tool used in the context of a specific curriculum to measure learning through verifiable performance-based metrics. Such systems are well-suited to medicine's needs. As eloquently stated by Issenberg et al, "evidence-based outcomes must show these systems to be effective instruments for teaching and assessment, and medical educators must be willing to effect change in medical education to ensure the appropriate use of these systems in the next millennium" (6).

Some terms that refer to the various dimensions of validation of an educational system may not be familiar to those entering this field. They are "face validity," "content validity," "concurrent validity," "discriminant validity," and "predictive validity." Basic definitions are as follows.

Face validity: Does the system look like what it is supposed to represent, ie, does it look like a fluoroscopy system if it's an interventional radiology training system? This is the easiest level of validity to accomplish. Testing is not required to establish face validity.

Content validity: Does the system measure the extent of knowledge that it is intended to measure, ie, does it contain the material that should be present for the training it intends to impart? This is a relatively easy level to meet.

Concurrent validity: Do the new system's results correlate with other measures proven to measure the same behaviors? For example, does performance on the new simulator correlate positively with skills or knowledge assessed by a validated oral test? Concurrent validity will be the first significant benchmark for systems to meet.

Discriminant validity: If a system is supposed to produce results that are different from those of another validated test, does it do so? Discriminant validity should follow from proof of concurrent validity.

Predictive validity: Does performance on the new system accurately and positively correlate with performance in an actual clinical situation? For example, if a trainee does well on the simulator, will that trainee also do well in a similar case on a real patient? For ethical reasons, this is the most difficult level of validation to accomplish and many systems will never be able to meet this level of validation, even though they are otherwise completely acceptable for training.

Some inaccurate phrases have entered the vernacular of medical simulation and should be discarded. Among these are "virtual-reality simulation" and "part-task trainers."

According to Rheingold (7) in his comprehensive early examination of the field, virtual reality requires two foundations: immersion through the use of head-mounted displays, stereoscopy, or other technology to create the illusion of being inside a computer-generated scene; and navigation through the use of data gloves or "computerized clothing," which enable the user to move around inside the artificial world. The term "virtual reality" comes to us from the entertainment world and pioneers like Morton Heilig, who were trying to create "experience theaters" and Sensorama, wherein a computer is used to create an artificial environment for amusement. In fact, Heilig patented this technology in 1962 (8). For medicine's purposes, a more accurate and precise term is "augmented reality," as our purpose is to add to our ability to interact with a computer-generated

scenario, allowing us to do what we cannot do in the real world. By these methods, we represent the real world as closely as possible to learn proper methods of treatment without putting patients at risk. Through computer-based simulation, a more accurate phrase for medicine's purposes, we do not create artificial reality, we augment reality.

The term part-task trainer has been used to describe a simulator that encompasses less than a full human mannequin, and which concentrates on one aspect of medical care such as laparoscopic skills training. The phrase originated in the early days of the simulation engineering community. However, the inherent inaccuracy in this term is immediately apparent to any medical practitioner: we do not consider our procedures to be tasks and no medical procedure is ever performed as a "part task." Medical procedures, whether starting an intravenous access or performing superselective catheterization of a vessel deep within the brain, are performed to completion as part of a larger therapeutic plan. To do less is to not practice medicine. For clarity and accuracy, we should speak of "medical simulation," not virtual reality, and "procedural simulation," rather than part-task trainers.

SIMULATION DRIVERS: EXPECTED AND UNEXPECTED

On August 31, 2004, the US Food and Drug Administration approved the marketing plan for one manufacturer's new medical device: a carotid stent (9,10). In earlier meetings, the company had been told that complication rates from stent use in the cervicocranial circulation presented a prohibitively high risk to the patient and that, before purchasing a stent, each physician must be trained to the extent of proficiency in the use of the device. The manufacturer was required to present a plan for training that did not involve patients in the earliest phase of the learning curve. The resulting five-part training program centered on simulation: after initial didactic and multimedia tutorials, multiple cases must be performed in a high-fidelity, physics-based simulation system and proficiency must be achieved on the simulator before the final stages of proctored deployment are permitted.

For the first time, a medical procedure was determined to be too risky to learn in the treatment of human subjects. Although the FDA decision related to marketing and sale of a device, the impact radiates outward to medical practice, as no physician of any specialty can use the device without proving safety and proficiency. The immediate beneficiaries of this decision are the patients.

However, secondary effects also arise from this decision. First, because proficiency can be objectified by simulator training, any physician of any specialty can become proficient in use of the device and then purchase it. The FDA decision is specialty-independent: all interested specialties are treated equally. In practical terms, this means that interventional radiologists, interventional neuroradiologists, interventional cardiologists, vascular surgeons, and even nonsurgical specialists such as neurologists can theoretically now present themselves as proficient in placement of a carotid stent to treat vascular disease in the carotid circulation.

Second among the effects of the FDA's decision is the fact that, by merely completing a training program on a simulator, a physician is not necessarily competent to perform the procedure in the absence of the other skills associated with making appropriate interventional judgments about the patient's care. A physician may be proficient in the use of a device and capable of deploying a stent, for example, in a correct fashion, but the same physician is not necessarily competent to perform that procedure. Competent care of a particular patient requires knowledge of the anatomy, pathophysiology, treatment effects, and overall clinical status of the patient. Simulator training may be necessary for proficiency, but simulator training alone is not sufficient for a physician to be certified as competent to perform interventional care. Simulator-based training is not a replacement for clinical experience.

Third, the full impact of the FDA decision has yet to be felt. Because a precedent has now been set that some procedures carry too high a risk to learn on actual patients, subsequent FDA approvals may also require training methods other than learning on humans: if one procedure is deemed too risky to learn on a patient, where does one set the bar for too great a risk? Is a three-times-greater complication rate in the early phase of a physician's training acceptable? Five times? Two times? No increase at all? When is a physician proficient? After 10 cases? One hundred? Therefore, this decision also impacts how we approach medical training throughout our careers.

Independently from the FDA decision, some malpractice insurers now reward physicians who have undergone rigorous simulation training by reducing their malpractice insurance rates. In Massachusetts, for instance, the Harvard Risk Management Foundation gives anesthesiologists and obstetrician/gynecologists in the Harvard system a 10% maximum discount annually if they successfully complete a 2-day risk-reduction course that involves team training simulation. This benefit has recently been expanded to physicians outside of the Harvard system who are insured by the region's largest insurance carrier.

Before the FDA's decision regarding safe use of a new medical device, the Institute of Medicine's landmark report, "To Err is Human" (4), created awareness of the issue of patient safety and the consequences of medical errors. The report called for, among other actions, the creation of new technologies that will make patient care safer. In Recommendation 8.1 of the Executive Summary of the report, the authors stipulate that health care institutions should establish interdisciplinary team training programs such as simulation that incorporates proven methods of team management, specifically in areas such as the emergency department, intensive care units, and operating room. Although the Institute of Medicine report focuses on team training as a means of reducing medical error, individual physician performance is also a critical element of patient safety (11), and procedural training with use of systems that provide performance metrics will create a powerful driver for early learning in a safe environment.

The American Board of Radiology, the Radiological Society of North America (RSNA), and the Society of Interventional Radiology (SIR) have

combined to form a task force on medical simulation, which has been charged with developing one voice and one plan for radiology's response to this technologic revolution in education. Discussions are now under way to include the Cardiovascular and Interventional Radiology Society of Europe as a part of this guiding group. This group is designing studies that will validate simulator use for radiology practice and will use the annual meetings of the RSNA and SIR to test the systems. This forward-looking commitment to a new educational model is part of an overall reevaluation of medical education in our specialty. Simulation will be used broadly throughout radiology and all of medicine. Although the present discussion emphasizes procedural education, institutions are already using simulation to train residents and faculty in management of contrast agent reactions individually and as part of a code response team, thereby improving the management of acute events in the radiology department. Most radiologists are required to maintain certification in Advanced Cardiac Life Support as part of their credentialing process. The Advanced Cardiovascular Life Support course, which follows a universally approved curriculum established by the American Heart Association (12), is a good example of the integration of simulation into an established curriculum. It is also an example of the use of simulation for routine refresher training to maintain skills proficiency.

Simulation's potential uses in medicine are still unseen; just as Edward Link could not have foreseen the many uses of flight simulation from his original Blue Box, even our visionaries are blind to the eventual uses simulation will find in the breadth of medical training across all levels, from first responders to experienced physicians. Procedural training and team training are the uses of which we conceive now because these are the tools we have to use; as more tools are designed for simulation, more uses will be found. In the near future, many training programs should be able to use simulator systems during residency and fellowship education, with the use of curricula specifically developed within the specialty to take maximum advantage of simulation's unique ability to "see and do what we could not see or do before." If these trials are successful, simulators may be integrated into the procedural subspecialty board examinations.

SIMULATOR DESIGN

The most critical requirement for simulator use is that effective learning must occur as a result of simulator training. In fact, this is the sine qua non of simulation. Learning implies a higher level of thought modification than training, and is best exemplified for our purposes by the illustration that training teaches the student that the left hand has to grip the catheter in such a fashion and the right hand has to apply torque to the guide wire in such a direction to successfully select a particular vessel. Learning why to do this is a higher function, and it is learning that defines simulation's greatest advantage for education: with a simulator, a student can practice over and over in an environment in which mistakes have no consequence for a patient. Simulation's "unfair" advantage is that it gives permission to err and to learn from those errors. But to do so, the simulator must be properly designed, and those design choices present an enormous challenge to the engineers, mathematicians, and computer scientists who create the system (2).

An endovascular training simulator is composed of several different subsystems, all of which must run simultaneously. Communicating among the different systems is necessary to account for and respond to the actions of the user in real time. The fact that each of these systems must run in real time is essential: belief in the simulator depends on realistic responses, and in a human, moving a catheter or injecting contrast medium does not occur with a half-second delay. However, a simulator does not have to reproduce every aspect of a procedure in exquisite detail. To do so at this time would be computationally crippling. Indeed, surgical simulators lag behind simulation in other specialties precisely because of this difficulty. Yet, a surgical training system that uses simple geometric abstractions of surgical tasks, the MIST-VR system (Mentice, Gothenburg, Sweden), has been proved to improve subsequent performance in the operating room (13). Optimization, the process of making careful choices in mathematical, engineering, and graphical algorithms, produces a system with sufficient realism that the student can enter into a state of suspension of disbelief. In medicine, every trainee approaches the system with a rich foundation of knowledge. The system must call up that knowledge and lead the trainee to a point of education that brings together the existing "data base" with the new challenge to be mastered (14).

In addition to the physical and graphical representations that are apparent to the casual user, a properly designed system includes a set of performance metrics that produce the proficiency measures to allow proof of learning. Ideally, these metrics are intuitively and transparently integrated into the simulation platform so the trainee can be quietly observed and correct and incorrect events can be recorded. However, efficient implementation of metrics requires that the designers work with the end-users from the first discussions of system design. In surgical simulation, for instance, observing surgeons and interviewing experts at the outset of the prototyping results in informed design of the final system, creating a simulator in which eventual validation of effective learning is simply performed (15). Such a system allows flexible data gathering so content validity, construct validity, and concurrent validity can all be assessed without elaborate data analysis. A well-designed system should be equally friendly to the user, the statistician, and the instructor.

Physics-based Design

No decision has a more profound impact on the eventual usefulness of a system than the concept of "physics-based design." A full discussion of physics-based design is beyond the scope of this introductory discussion, but a simulator that is physics-based responds appropriately to the user regardless of the maneuver that is performed. If a student makes an error, a physics-based system allows the error to occur and tracks the resultant effects in the other subsystems, such as physiology, graphical display, and instrument position. The advantages of

such a system arise from the design: because the system reacts transparently to the user's choices and actions, correct and incorrect choices are equally possible. Complications can occur, and more importantly, bad habits are not perpetuated. A bad simulator is worse than no simulator at all, and one that imparts bad habits is dangerous. If a system is designed to behave according to the rules of physics, physiologic responses are appropriate and correct and incorrect actions are properly represented to the user.

A non–physics-based system allows errors to occur without consequence. This is obviously unacceptable in an educational device. Our goal in simulation is to remove the patient from the early learning curve of the trainee. If we create a simulator that teaches bad habits, our patients will suffer the consequences, and that is an unacceptable result. Effective simulation creates more than an elaborate video game. The most difficult task in creating procedural simulators is to build a physics-based system (16). Everything else in the system follows the physics.

VALIDATION AND TRIALS

As procedural simulators are developed, validation studies are being performed to assess their learning efficacy. In a landmark article, Seymour et al (13) reported a randomized double-blind study examining resident performance during laparoscopic cholecystectomy, comparing groups who used an early surgical skills training system versus those who operated without simulator training. Those residents who received simulator training performed clinically with the correct dissection technique, six times fewer predefined intraoperative errors, more consistent progress during surgery, and 29% shorter operative times.

Other studies are beginning to establish curricula that incorporate simulation as a core element of a comprehensive training experience and a means of reducing technical errors globally. In a multiinstitutional study, Fried et al (17) assessed the performance of medical students, residents, and faculty who used an early endoscopic sinus surgery simulator and established the transference of skills training from one simulator (MIST-VR; Mentice) to another (ES3). This group also emphasized the framing of simulation within a curriculum of proficiency-based training that strives to create a learning environment in which residents train to meet objective standards of proficiency before being allowed to treat patients. They recognized the changes that such a shift in learning would impose on established residency programs, but also indicated that this curriculum instilled a "culture of safety" within the institutions that participated in the program. Similar desirable effects can be expected through careful, rigorous adoption of procedural simulation broadly across specialties.

Rigorously controlled trials are under way in endovascular specialties to compare simulator training versus no simulator training among highly experienced physicians; these trials also examine the learning curve and performance of physicians who are procedurally naive. Results of those trials will help shape the discussion and decisions on the proper role for procedural simulation in residency and fellowship programs in the United States and elsewhere.

POTENTIAL ROLES OF SIMULATION

Simulation should augment existing training curricula rather than being seen as a replacement for our present methods. Its greatest power lies in the ability to "see and do what we could not do before," as stated by Oriol. When we have examined the possible roles, we can begin to insert this powerful tool at many different levels throughout medicine, just as aviation uses simulation for more than simply showing a pilot how to control an airplane. Some of the likely roles for simulation are as follows.

Aptitude Testing

Students at all levels can examine medicine as a career option through practicing procedures or learning simple medical techniques. At the graduate level, simulation could be used to assess an individual's native skill and aptitude for particular specialties. Such use would obviously incur many ethical questions, as native skill and acquired skill might not be equally valid predictors of eventual practice success.

Early Skills Acquisition

At the medical school level, courses such as the Gilbert Program in Medical Simulation at Harvard Medical School are already used to correlate anatomy with function and to teach diagnosis and therapy to medical students. Faculty members carry a beeper and students can call the simulation faculty for impromptu sessions on clinical management of arrhythmia management or treatment of airway disease in a realistic simulated clinical environment (18,19).

Advanced Skills Training

When a new procedure is developed or when a new monitoring device is designed, simulation can be used to train experienced personnel in the method of practice or appropriateness of the procedure or device. This role closely parallels the use of aviation simulation to train experienced flight crews in the characteristics of a new avionics package in an aircraft that is familiar to them.

Career-long Training

For established physicians, the most practical use of simulation may be related to the ability to learn a procedure that was invented after the physician's postgraduate training concluded. Currently, physicians of many specialties are learning to perform carotid interventions with use of simulation, thereby avoiding patient exposure early in their learning curves. Similarly, physicians may return to a simulator after prolonged absence from practice to regain proficiency. State medical boards are already examining the use of simulator training to assure that physicians with high loss profiles meet minimum practice expectations, or for remedial refresher training after an adverse legal judgment.

Board Examination

Some specialties may become early adopters of simulation for board ex-

amination. Interventional specialties like radiology or cardiology can use simulation to transform an oral examination from a verbal description of how a procedure is performed to actual observation of how a candidate performs a procedure. Those candidates who are particularly adept will immediately become apparent, as will those who are less gifted. Complications that occur during a case can be managed during the examination process. Although some would argue that this type of change would put the candidate in an even more stressful situation during the examination, the countervailing argument is that it will also create an examination situation that more closely approximates real-life practice. When candidates are aware that they will be required to perform specific cases in a simulator for their qualification examinations, they will be likely to familiarize themselves with the simulator during their training programs. As Dillon et al (20) noted in a discussion of the future of medical simulation for medical licensing, "once there is evidence to support the use of scores from these [systems], these new simulation modalities will certainly be embraced." The work of producing the evidence falls to us.

Credentialing

Hospitals currently grant privileges to practice based on training documentation and letters of reference. In the future, simulation could allow the chief of the sponsoring department to examine the performance of a candidate to assure that desired levels of practice quality are maintained.

Preprocedural Rehearsal

The ability to rehearse a specific patient's procedure before actually performing it on the patient requires that the simulator be able to accept digital data and represent that data faithfully, including all relevant aspects of pathophysiology. This presents an enormous computational burden on the simulator's design and requires that the entire system be physics-based. However, patient-specific simulation is an achievable near-term goal. Procedure rehearsal with patient-specific data requires a time commitment from the physician, and will therefore be used to different extents by different physicians: those with less skill may find more use for practicing a procedure before performing it on the patient, whereas more experienced physicians will likely use the simulation for only cases in which atypical anatomy or a particularly difficult pathophysiologic conditions will be encountered. Every physician has the same 24-hour day, so procedure rehearsal will have to prove its worth to many skeptical users before it becomes a routine clinical event.

Procedural Prototyping

A simulator that is based on fundamental mathematical and physics principles applied to representation of medicine will allow a completely new meaning for the phrase, "the practice of medicine." With such systems, innovators can engage in "what-if" scenarios, experimenting with novel ways to treat disease or deploy devices. In a physics-based simulator, physiologic changes brought about by a new way to perform a procedure can be examined and favorable or unfavorable responses can be examined in a risk-free environment. Although current simulation uses are centered around training, a few early adopters are beginning to explore the unique opportunity that simulation can provide in the performance of experiments that were previously inconceivable in a practical sense. As mentioned previously, simulation will let us do and see what we could not do or see before. Medicine will have to learn to use the potential it affords us.

Replacements for Animal Laboratories

Galen performed animal dissections in Rome nearly 1,000 years ago to teach anatomy. For the next 1,000 years, there were no options to animal laboratories for early learning. Although it is not a primary driver behind the development of simulation, one of the immediately apparent advantages of the technology is the ability to switch from animal laboratories to computer laboratories for learning. Even when animal facilities are available, the particular disease to be treated frequently has no realistic animal analogue, requires chronic dietary alteration to provoke the development of a reasonable facsimile of the human condition, or requires training on an animal model that is unsuited for transfer of learning to human pathophysiology because of animal size or lack of comparable anatomic models. In a simulator, the anatomy is based on graphically similar representations of the human condition or is taken directly from patient-specific data, so fidelity is extremely high. Procedures can be practiced repeatedly by one or many trainees without any degradation in the quality of experience or injury to the "subject." Simulation allows a learning experience to be repeated, allowing errors to occur and to be "trained out," in stark contrast to animal laboratories, in which there is frequently only one chance to perform a procedure, and if errors occur, they are difficult to "train out" without the use of many animals. In addition, simulators can provide performance metrics that cannot be obtained through animal use. In countries in which animal use is restricted, simulation offers an important alternative to human use for learning early and advanced skills.

VISION

Edward Link's first flight simulator was not fully adopted until nearly 15 years after it was developed. No controlled trials were required before the military recognized that simulation made sense. No one died while learning to fly on a simulator, but many pilots did not die when they landed on a carrier at night after using Link's simulator to practice. During the past 75 years, we have invested tens of billions of dollars to make flight simulation as effective as it is today. We should not expect an instant acceptance of medical simulation, nor should we expect to realize the gains it can provide without a sizable investment in its creation and implementation into our training curricula. However, we must not let the absence of proven efficacy in double-blind trials delay the beginning of our adoption. Some things just make sense. We must begin.

The future of procedural education must adjust to the fact that medical practice has changed since residency structure was outlined by Halsted in the early 20th century. No longer are

patients in the hospital for prolonged periods, during which physicians in training, of all specialties and at all levels, have ample "contact time." Procedures have migrated from the inpatient setting to outpatient clinics, and in some cases, to freestanding centers unaffiliated with teaching hospitals. At the same time, patients have become more erudite: many patients now arrive at the physician's office having researched their symptoms and with a list of presumed diagnoses. They know the best physicians to treat their condition, and in some cases, they even have hospital performance data for a number of local institutions. Halsted never foresaw this day.

Simulation will be adopted by medicine, but the history of traditional learning in the master/apprentice system that has existed since ancient Egypt will not vanish easily: our entire teaching hospital structure is built around a reliable supply of residents who are available 24 hours a day, 365 days a year. In Halsted's vision, there were no workforce guidelines or Accreditation Council for Graduate Medical Education restrictions limiting residents to 80 hours a week of patient care and on-call time. Indeed, if Halsted were alive and proposing his system in today's training environment, the term "resident" for a physician in training would never have come to mind.

Physicians must work alongside those in the educational sciences to create studies that will prove or refute the ability of simulation to effectively train physicians and other health care providers. We must demonstrate that the training acquired through simulation transfers to patient care. When this is accomplished, our educational curricula will be rewritten to incorporate simulation as a stand-in for actual patient contact during early learning, when physicians are at the greatest risk of committing an error. Simulation will help mitigate the unevenness of case mix inherent in the trainee's finite experience in a single training program. The overall educational experience for every resident will become more homogeneous and no longer subject to random variation in the availability of case material. Then, advancement through physician training will truly be based on the achievement of milestones rather than length of time in service. Simulation will also change the way complications are corrected because it will allow errors to occur "in silico" instead of in vivo. Today, when a faculty member trains a resident or fellow, the two work together to correct the consequences of any errors that occur, and only that particular trainee benefits. Simulation will allow an entire library of errors and consequences to be archived so all trainees can experience, in a simulated sense, the firsthand experience of fixing their mistakes.

CONCLUSION

Because a "smart simulator" is designed to be intuitive and transparent to the user, performance on such a system can closely approximate actual clinical conditions. Instructors can evaluate a trainee's performance over time and under various conditions. The learning curve can be established for each trainee and those with particular expertise can be identified, as can those whose particular liabilities require further training. Through such physics-based simulation systems, the full potential of simulation can be realized, and medical training can move from the traditional model of fixed-length residencies to proficiency-based learning. Not only will we be able to identify and accelerate the training of residents with exceptional ability, but we will be able to improve patient safety by identifying those few trainees for whom the calendar is not the most appropriate measure of ability.

To render errors without consequence to patients, to learn from those errors, and to practice on a realistic system until they are eliminated: these are the defining abilities of simulation that will enable the coming revolution in medical education. The ultimate beneficiary of this revolution will not be the physician; it will be our patients.

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References

1. Long DM. Competency-based residency training: the next advance in graduate medical education. Acad Med 2000; 75:1178–1183.
2. Dawson SL, Cotin S, Meglan D, et al. Designing a computer-based simulator for interventional cardiology training. Cathet Cardiovasc Intervent 2000; 51: 522–527.
3. Klein LW. Computerized patient simulation to train the next generation of interventional cardiologists: can virtual reality take the place of real life? [editorial] Cathet Cardiovasc Intervent 2000; 51:528.
4. Kohn JT, Corrigan JM, Donaldson MS, eds. To err is human: building a safer healthcare system. Washington, DC: National Academy Press, 1999.
5. Cooper JB, Taqueti VR. A brief history of the development of mannequin simulators for clinical education and training. Qual Saf Health Care 2004; 13(suppl 1):i11–i18.
6. Issenberg SB, Gordon MS, Gordon DL, et al. Simulation and new learning technologies. Med Teach 2001; 23:16–23.
7. Rheingold H. Virtual reality. New York: Simon and Schuster, 1991.
8. Heilig M. US Patent number 3,050,870; 1962.
9. US Food and Drug Administration, Center for Devices and Radiological Health, Medical Devices Advisory Committee, Circulatory System Devices Panel meeting. Available at: http://www.fda.gov/ohrms/dockets/ac/04/transcripts/4033t1.htm. Washington, DC: FDA, 2004. Accessed November 19, 2004.
10. Gallagher AG, Cates CU. Approval of virtual reality training for carotid stenting: what this means for procedural-based medicine. JAMA 2004; 292:3024–3026.
11. Shah RK, Kentala E, Healy GB, et al. Classification and consequences of errors in otolaryngology. Laryngoscope 2004; 114:1322–1335.
12. ACLS Provider Manual. Dallas: American Heart Association, 2004.
13. Seymour NE, Gallagher AG, Roman SA, et al. Virtual reality training improves operating room performance: results of a randomized, double-blinded study. Ann Surg 2002; 236:458–464.
14. Shaffer DW, Dawson SL, Meglan D, et al. Design principles for the use of simulation as an aid in interventional cardiology training. Minim Invas Ther Appl Technol 2001; 10:75–82.
15. Stylopoulos N, Cotin SM, Maithel SK, et al. Computer-enhanced laparoscopic training system (CELTS): bridging the gap. Surg Endosc 2004; 18:782–789.
16. Dawson SL. A critical approach to medical simulation. Bull Am Coll Surg 2002; 87:12–18.
17. Fried MP, Satava RM, Weghorst S, et al. Identifying and reducing errors with surgical simulation. Qual Saf Health Care 2004; 13(suppl 1):i19–i26.

18. Gordon JA, Oriol NE, Cooper JB. Bringing good teaching cases "to life": a simulator-based medical education service. Acad Med 2004; 79:23–27.

19. McMahon GT, Monaghan C, Falchuk K, et al. A simulator-based curriculum to promote comparative and reflective analysis in an internal medicine clerkship. Acad Med 2005; 80:84–89.

20. Dillon GF, Boulet JR, Hawkins RE, et al. Simulations in the United States Medical Licensing Examination (USMLE). Qual Saf Health Care 2004; 13(suppl 1):i41–i45.