Surgeons must learn to perform operations. The current system of surgical resident education is facing many challenges in terms of time efficiency, costs, and patient safety. In addition, as new types of operations are developed rapidly, practicing surgeons may find a need for more efficient methods of surgical skill education. An in-depth examination of the current learning environment and the literature of motor skills learning provides insights into ways in which surgical skills education can be improved. Computers will certainly be a part of this process. Computer-based training in technical skills has the potential to solve many of the educational, economic, ethical, and patient safety issues related to learning to perform operations. Although full virtual-reality systems are still in development, there has been early progress that should encourage surgeons to incorporate computer simulation into the surgical curriculum. Arch Surg. 2000;135:786-792

Continual advancements in technology have dramatically changed the ways in which we conduct our daily activities. Likewise in the practice of medicine and surgery, technological advances during the past several decades have had an enormous impact on the ways in which we diagnose and treat disease. In contrast, our methods of teaching surgeons to operate remain mired in the 100-year-old Halstedian apprenticeship model. In this system, surgeons often learn to operate on the principle of “see one, do one, teach one,” relying heavily on chance for educational opportunities. A patient with a specific disease must present to achieve a particular educational goal. The Halstedian-based system of resident education has produced generations of fine technical surgeons and has provided for quality patient care. However, changes in health care provision and the development of new surgical technology are challenging this system.

Computer-based surgical simulation, often referred to as virtual reality (VR), holds enormous potential for enhancing surgical training. Many reviews and reports on this topic rely heavily on the successes achieved by the military and aerospace industry as reasons for adopting VR for surgical training. Although the parallels and analogies between aviation, the military, and surgery make intuitive sense, we wish to introduce other rationales for VR. Herein, we describe a number of educational challenges, discuss the learning factors involved, and provide some solutions based on the capabilities of modern computing power.

CHANGES IN THE CLIMATE OF SURGICAL EDUCATION

Several factors aside from costs are affecting surgical training. The hospital inpatient population is changing as a broader range of diseases is treated surgically and the therapies become more complex. In insurance payers have, in effect, promoted less independence of housestaff by requiring better supervision by faculty members. Residents are asked to learn more diseases and operations in the same number of (or fewer) working hours. Learning diseases and operative technique by random chance and opportunity will become increasingly difficult if (as one would expect) these trends continue.

These challenges extend after the 5 or so years of surgical residency. Practicing surgeons encounter many of the same issues. For example, many practicing surgeons completed their training before the
so-called laparoscopic era of the 1990s. These surgeons have therefore found venues other than residency programs for training in laparoscopic operations, possibly long after completion of their formal training, often while maintaining a busy practice. Costs and outcomes for this group are equally important. As in surgical residency, solutions to these problems may become more difficult as technological advances in surgery continue.

Although cut, sew, and tie remain the staples of surgical craft, laparoscopic or minimally invasive surgery (MIS) has changed forever the way many operations are performed, and may herald the beginning of an era of hyperrevelation in surgery. At present, we are witnessing the emergence of robotic-assisted operations when the field of advanced laparoscopy is relatively young and still under development. We have conceptualized this as a pyramid model of compounding technology (Figure 1), designed to illustrate that recent advances in surgical technology have been built on and modeled after more traditional techniques. The pyramid implies that a base of skills in traditional techniques must be established before moving on to newer and often more remote and foreign skills. In this model, laparoscopy resembles and builds on open techniques, whereas robotic-assisted surgery builds on laparoscopy. The question mark indicates that there are procedures and techniques yet to be developed.

Taking this model further, it indicates that residents and practicing surgeons not only need to learn the operations performed by their predecessors, but to learn entirely new and different types of skills and procedures. At present, mastery of more established techniques is required before moving up to new types of operations. Surgeons need to have skill in traditional techniques before learning MIS. In an era of compounding technology, the acquisition of new sets of different skills may be necessary multiple times during the course of a career. For these reasons, the same pressures encountered during surgical residency apply to practicing surgeons.

THE OPERATING ROOM AS CLASSROOM

In today’s surgical residency programs, most education in surgical skill takes place in the operating room (OR). Some have argued that the OR is the best classroom for surgical education. There may never be a replacement for the live situation of the OR as the final environment for learning to perform operations. In many ways, however, the OR is a poor classroom for learning surgical skill. By necessity, there are numerous distractions, most having nothing to do with education, that take priority (patient issues). In general, the opportunity for teaching is underused. The learner may arrive exhausted or unprepared because of other duties. The surgical mentor may not be a good instructor. Some learners may view the OR as an uncomfortable, stressful, or even hostile educational environment.

In the OR, the teaching session cannot always be well designed or predicted. Again, the primary focus has to be on care of the patient. The case at hand may not be well suited for the learner. The technical requirements may be well above or below the learner’s abilities, so that the experience in the OR is not educational. The progress or sequence of the operation cannot be altered to satisfy educational goals. Dissection and exposure cannot be performed for demonstration only. Steps may not be repeated, and the patient cannot be reassembled to start over if failure occurs.

An important consideration is that the OR is a suboptimal classroom in terms of the stress-learning relationship, since the OR is often a very stressful environment. There has been considerable work this century studying the effects of stress on learning potential, beginning with the studies of Yerkes and Dodson in the early 1900s. This bell-shaped curve of stress vs learning and performance potential (Figure 2) also has been called the “inverted-U principle.” Investigators have found that the greatest learning and performance potential occurs in an environment of moderate stress. Furthermore, in situations requiring fine motor control and complex cognition, low stress or arousal levels enhance performance. A number of factors contribute to a high level of stress in the OR, eg, time constraints, technical difficulties, concern for the patient, equipment failures, interpersonal issues, and the handling of telephone calls about other patient issues.

The OR is also an expensive classroom. Bridges and Diamond examined the effect of the presence of residents in the OR. They calculated that the nonsupply costs

Figure 1. Pyramid model of compounding technology. Never technology requires different and more remote surgical skills.

Figure 2. Yerkes-Dodson law. Environments of low or high stress are suboptimal for learning and performance.
for general surgery residents alone was $53 million annually in the United States. We suggest that when considering all other trainees in the OR, including other surgical trainees, nurses, and anesthesiologists, the cost on a national level is enormous. Hospitals and institutions are becoming more aware of the cost of training and are urging surgeons to conduct their operations more expeditiously. One simple method of compliance for the teaching surgeon would be to decrease teaching or resident operating time.

Cost must also be considered in terms of risk to the patient. Ideally, surgical training on any level would always occur under the guidance of an experienced surgeon, so that the trainee is kept in check. This may not always be the case. Again, the surgeon beyond residency attempting to incorporate new skills must be considered. It is unlikely that the surgeon in practice will always have an appropriately experienced mentor available to ensure an optimal technical result.

SURGICAL SKILL

In 1983, Spencer⁵ wrote, “Probably about 75% of the important events in an operation are related to making decisions, and about 25% to dexterity.” Although this statement contains a certain truth, there are several ways to look at this from the standpoint of technical skills education. The surgeon may need to develop a number of different skills for different procedures, but good basic judgment applies in many circumstances. Furthermore, successful completion of any operation ultimately depends on technical execution. Indeed, surgeons have been able to predict a worse postoperative course for their patients based on technical factors alone that occurred during the operation.¹⁰ Another study has shown the surgeon's “gut feeling,” including technical factors, at the end of a case can predict postoperative complications.¹¹

Other ways in which judgment and dexterity are related are that (1) judgment may be clouded during a technical struggle, (2) the operating surgeon may find it difficult to learn or to execute good judgment while focused on basic technical maneuvers, and (3) these combined factors may be more pronounced in the case of the training surgeon. The following example helps illustrate these points: Given a senior resident who is struggling with the technical basics of the operation (e.g., knot tying), there can be little hope that the resident will learn surgical decision making or the finer points of the operation. Since surgical judgment is so important, shouldn't the senior resident in question be learning judgment rather than knot tying while in the OR with the master surgeon?

Surgeons certainly recognize the importance of technical skill. Not surprisingly then, there has been interest in testing that would permit selection of individuals based on abilities, for surgical training. Ideally, testing would identify those individuals with some previously undefined aptitude for performing operations. It can be frustrating for a surgical mentor to teach a resident who does not seem to “get it,” implying poor technical skills. To date there can be no consensus on a particular test that will permit selection for those who will go on to become proficient surgeons. There have, however, been some provocative findings to come out of this work.

At this point, it is worth differentiating abilities from skill. Consistent with the educational literature and concepts of motor-skill learning, abilities will be defined as inherent or innate. Skills, on the other hand, can be learned and refined. A student enters a learning situation with varying degrees of abilities. Through practice and training, skills are then developed.¹²

VISUOSPATIAL ABILITY

A fairly straightforward assumption would be that individuals demonstrating surgical proficiency would have above-average inherent psychomotor abilities. Several groups have tested this hypothesis and discovered concepts there is no difference in pure psychomotor ability between residents and practicing physicians, whether internists or surgeons.¹³⁻¹⁵ Further testing, however, in these and other studies has shown that a trait known as visuospatial ability correlates with a higher level of surgical skill.¹³⁻¹⁷

Visuospatial abilities relate to the ability to represent a 3-dimensional situation mentally using key landmarks and to have a clear mental picture of their relationship in space.¹⁸ Visuospatial analysis also may be thought of as the ability to distinguish the important points in a complex environment where the noise level is high. Although these traits would certainly be of use to someone who works in a complex 3-dimensional world (the human body), often under stressful situations, the issue remains of how visuospatial skills make a difference in the development of technical skill.

The schema theory of motor skill learning by Schmidt¹⁹ suggests that visuospatial ability and the acquisition and development of motor skills may be closely related. Schmidt's theory emphasizes the learner's expected and observed consequences during task performance. Learners with enhanced visuospatial ability may then be able to generate more accurate and rich mental 3-dimensional representations of the expected and observed consequences during motor performance. These learners also may be able to store a more sophisticated collection of motor skills, all built on a finely detailed 3-dimensional interpretation of the environment. Through continual comparison of a mentally generated set of expected 3-dimensional consequences with an enhanced observation of the 3-dimensional world, faster and more accurate motor skills may be developed.

HOW SHOULD WE TEACH?

Based on these observations, there are reasons to examine the current surgical education system and to look for solutions. Ravitch²⁰ states, “Residents, now for the most part in university programs, are, in fact, graduate students, although in most cases receiving no degree. What other graduate program in the university is almost totally without course instruction?” Today many surgical residencies have nonexistent or loose curricula for technical skills training. There is no doubt that it is difficult to find time for purely educational activities amid a busy
residency or practice. The service demands are endless; the educational opportunities, few. However, surgeons in residency and practice alike need to realize that a formal program for technical skills training is a necessity rather than a luxury. Surgeons in the community will need to build this time into their own practice. In residency programs, it will ultimately become the responsibility of the chairman and program director to ensure that the residents have time away from clinical duties for educational purposes.

Surgeons as educators should examine their roles and obligations continually. Several authors describe characteristics of an excellent teacher of operative performance. The mentor must adhere to basic and sound surgical principles. The student must be recognized as an adult learner with varying goals and amounts of ability and motivation. Objectives should always be clearly defined and understood by the student and the mentor. The mentor should understand that surgical performance is multidimensional and that an individual student may be proficient in certain skills while lacking in others, thereby inhibiting overall improvement. Possibly the most important factor in good mentoring is physical presence in the learning environment, demonstrating interest and commitment to the students' education. In this setting, the mentor can observe carefully, provide constructive feedback, and exhibit patience and positivity.

LEARNING OUTSIDE THE OR

Improvements may be made in the setting where surgical skills are taught. As described earlier, the OR can be a poor classroom for surgical skill training. An alternative environment is a large part of the solution. Many experienced surgeons often refer to their attempts to learn surgical skill as students or junior residents outside the OR as “tying knots on the bedpost at night.” Whether literal or figurative, this phrase describes the practice in basic skills occurring outside the OR. These individuals certainly had the motivation and desire to learn surgical skill so that they could perform at their best when the chance arose in the OR. This type of training must be recreated for all students of surgery to include basic as well as advanced technical skills.

There are tremendous advantages to training outside the OR. Probably the most important factor is that the learning environment is more easily controlled and adjusted. Each learning situation can be tailored for each student’s needs and can be altered on a minute-by-minute basis to create the desired effect. The student would not be forced to participate in an entire procedure to cover key basic technical skills objectives. In addition, learning can occur in a more stepwise fashion. Figure 3 shows a pyramid model for training outside the OR. As a level of skill is mastered, the student may then proceed to the next level, building on previous accomplishments. The pinnacle of this structure is skills training in the OR.

The most basic approach to begin learning surgical skill that can be transferred to the OR would be to learn the basics of technique or task analysis and performance. Every complex surgical procedure can be broken down into several simple tasks that are required to complete most of a complex operation. Many young students of surgery recognize that efficient and reliable knot-tying techniques will be useful in many facets of surgery, hence “tying on the bedpost.” Other basic tasks can be defined for cutting and sewing as well. Rosser has popularized an excellent teaching module for laparoscopic surgery. What have come to be known as the “Rosser stations” among surgeons learning laparoscopic techniques are 3 simple tasks that teach specific skills required for basic laparoscopic surgery. These tasks are designed to teach 2-handed technique, coordination in handling tissue, and facility with manipulation of a sewing needle, all of which are important in performing laparoscopic operations.

A second level of training, which can then be added to the basic task skills, will be visuospatial training. Earlier, the importance of visuospatial abilities was emphasized, although these are inherent and innate to the learner. It is not known if visuospatial skill can be taught in a similar way that motor skill development can, or if visuospatial skill training can enhance technical performance. Perhaps visuospatial skill acquisition is an important but unrecognized component of learning to operate. If visuospatial ability is more important than psychomotor ability, then it is possible that visuospatial skill is more important than motor skill in surgical proficiency.

Regardless, we wish to assert the concept of strong emphasis on instruction at this level in 3-dimensional relationships of anatomic structures and surgical maneuvers. Visuospatial training begins with a clear understanding of normal surgical anatomy. This can then be expanded to teach skills in pathologic anatomy, key relationships of vital structures, and dynamic anatomy during an operation.

Building on these skills, the learner can then proceed to the practice of the setup and exposure. These skills for performing operations are probably underappreciated by novices but treasured by experts. When these skills are not well developed, poor exposure and a technical struggle ensue. These important skills incorporate visuospatial information while keeping the next proce-
dural components in mind. The sequential steps of the operation become much easier when proper setup is used.

Finally, an environment can be created where the student practices larger procedural components of the operation or the entire operation from start to finish. The procedural components are common to many operations, including placing a laparoscopic port, dissecting out a major blood vessel, and performing a bowel anastomosis. Procedural components such as these can be practiced over and over outside the OR so that the setup and performance would be almost automatic.

An operation performed in a practice environment ideally may be practiced repeatedly, until proficiency is achieved. Additional factors may be introduced to aid in the learning experience. It may be required that the student perform the operation in a limited amount of time, thus increasing stress, possibly simulating the real OR more accurately. Additional challenges such as limited exposures or difficult technical situations also may be introduced to achieve the educational goals.

**HOW CAN THIS BE ACCOMPLISHED?**

The cost and logistics of creating such a learning environment may be staggering. During an actual operation it is difficult, if not impossible, to completely separate out levels of learning objectives. At present, most structured technical skill courses outside the OR make use of inanimate (latex) or animate (porcine or canine) physical models. In addition to the ethical considerations in using animals for training purposes, there are other substantial limitations. Dedicated physical space must be available, especially when using animals. In addition to the cost of the animals and synthetic models, other equipment, such as surgical instruments and supplies, must be available and functional. This may include sutures, scalpels, laparoscopic ports and instruments, and video equipment. Maintaining these resources so that they are available on demand for the learner is generally prohibitively expensive and time-consuming.

Computer-generated surgical simulation, or VR, for technical skills training has the potential to solve many of these problems. Simulation allows learners to participate in real-life events without significant risk.23 In a computer-generated virtual model, there is no patient who might suffer. Task performance or any particular learning module may be repeated as many times as necessary. The simulated operation may be abandoned if the student reaches a point of fatigue or saturation. The desired end point of the task or the operation can be changed continually to meet the learner’s needs. In this setting, trainees can inflict numerous injuries, causing numerous complications time after time, if necessary, to achieve the educational goal. This learning environment can be structured for maximum convenience. Learners would not have to wait for a particular case but would practice whatever and whenever is best suited to their needs. Going even further, the computer may “sense” when the learner is saturated or “know” what degree of challenge to present to the student.

Virtual reality holds tremendous promise for the future. Computer systems may be almost as convenient as a text or atlas. All of the equipment required to perform a virtual task or procedure may be contained on a desktop within the computer-generated environment and interface system. These systems are especially well suited to training of video-assisted procedures so that the computer monitor substitutes as a video monitor.

Computer-generated models would be the perfect practice patients. Computer-modeled organs can be shown or hidden as part of visuospatial training. Any structure can be viewed in its relationship to any other structure. The structures can be rotated in 3 dimensions for analysis of the relationships from any angle. The student can study how retraction and exposure facilitates identifying correct anatomy and establishes a comfortable operating setup in which to work. The student will be able to see structures rarely visible during the actual operation and be able to appreciate key anatomic structures. Variable transparencies may be assigned to tissues so that hidden structures, which are otherwise avoided, can be seen and also appreciated.

The student could be penalized for poor exposure and setup as in real life. The student may not be able to visualize or access all pertinent structures if the incision is of insufficient length or improperly placed. He or she may be able to experiment with a number of different port-site configurations in a laparoscopic simulation. If the student finds that the computer simulation of the operation does not adequately demonstrate the necessary anatomy, the student could then quit that scenario and go to an explanation of the proper setup for the operation.

After progress is made in task performance and exposure, the student may progress to the level of performing entire operations in VR. At this stage, all of the previously learned skills culminate so that the student can practice the operation with as much realism as possible, including force-feedback, ie, the ability to “feel” the interaction with the virtual tissues. In this stage, the student must have acquired some mastery of the basic technical skill germaine to the operation at hand. The student must have an appreciation for the anatomic structures and relationships. The student has also received instruction on the setup of the operative field. At this level, the student will practice combining all of these factors while practicing the sequence of events that must occur to achieve the result of a successful operation. At this stage, it may also be possible to incorporate patient-specific data as part of the surgical rehearsal.

Modulation of stress in the learning environment should receive a great deal of emphasis when considering computer simulation. As stated earlier, the potential for learning decreases in situations of very low or very high stress, whereas a low or moderate level of stress promotes the best environment for learning operations. It would be almost impossible to focus on and maintain an optimal stress level for learning in the OR. Here again, computer simulation may provide the answer. Many basic skills could be practiced in the environment of VR, with moderate levels of stress and more effective learning. Surgeons would then be better prepared for the real OR after practice in VR. Reduction of student stress in the OR may be accomplished though maximum prepa-
ration outside the OR. Computers therefore may provide a 2-fold benefit in the stress-learning relationship by enhancing learning in a stress-optimized virtual environment and increasing learning in the OR in a setting of reduced stress through better preparation. In a sense, both environments (Figure 4) are optimized in terms of the stress-learning relationship. Stress may also be increased if this is desired to meet the learning objectives.

Although VR holds tremendous promise for the future, current systems require further development and refinement. Photo-realistic, force-feedback capable, real-time VR systems that permit total immersion are not yet available as teaching tools for technical skills, largely because of the enormous computing power required to run these systems. However, as computing power continues to double every 18 months, it is expected that these environments will be possible in the near future. Nonetheless, strong consideration can be given to computer-based training devices now as well as in the future.

Computer-generated simulations are available today that hold promise for teaching technical skill, while not providing the total suspension-of-disbelief VR experience. These trainers use relatively simplistic input devices that enable the learner to manipulate cartoonlike virtual objects. Virtual task performance is achieved at the expense of photo-realism and force-feedback, thereby reducing computing power requirements. Other trainers focus on more simplistic but complete procedures. Rather than attempting to simulate an entire major operation, these devices involve skills related to intravenous catheter insertion, flexible endoscopy, and basic laparoscopy. The actual simulators, as well as the technology that drives them, are under constant and rapid evolution. A reliable annual update on state-of-the-art surgical simulation can be found in the proceedings from the Medicine Meets Virtual Reality meeting.26

ISOPERFORMANCE

Despite all of the practice that can be achieved in a virtual environment, training ultimately will have to occur in the real OR. Likewise, regardless of the realism and the suspension of disbelief that can be achieved in VR, skills will need to be refined on real patients under the guidance of a surgical mentor. By having had some experience with the procedure in question in VR, however, better preparation and better learning in the OR are expected. Jones and Kennedy27 have used the term isoperformance in the field of applied psychology. Isoperformance in this sense and in the teaching of a particular skill means that learning by 2 different methods will transfer the same skills, albeit with different efficiency.

Pertinent to the field of surgery is the work that Jones and Kennedy performed in drawing an isoperformance curve from the raw data collected by Roscoe from flight training in the 1970s and 1980s (Figure 5). Roscoe showed that certification in a particular flight task required a certain number of hours of training. The students he studied spent variable amounts of time in actual flight and some amount in simulation training in this task. When plotted on x- and y-axes, a curve is generated demonstrating, to a point, that trainees could reduce the number of actual in-flight hours of training by spending time in a simulator. For example, from the figure, if the trainee spent 0 hours on the simulator, one would expect that the trainee would need to spend roughly 10 hours in actual in-flight training for certification. However, if the student spent 3 hours in the simulator, only about 6 hours of in-flight training would be necessary. In the latter example, the total time spent training was less when the simulator was used when compared with in-flight training only.

In this example of isoperformance, trainees were able to reduce substantially the number of in-flight training hours by spending at least some time in the simulator. We would expect that the simulator training was more convenient, cheaper, and safer than in-flight training. Similar results for simulated surgical training may be possible, especially if effective and efficient teaching tools can be developed for VR training.

Again, computers may offer a 2-fold benefit by providing efficient training outside the OR while increasing the efficiency of training inside the OR through better preparation of the learning surgeon. As mentioned before, during a busy surgical residency or surgical practice, finding time away from clinical service to train is
often difficult. The goal would be to show a decrease in the live patient practice time (and possibly total practice time) necessary to become proficient at a particular procedure. As more experience is gained with VR and training outside the OR, isoperformance data for these new methods will be generated, establishing their relative effectiveness.

CONCLUSIONS

The Halstedian method of training has produced many generations of fine surgeons. Consisting largely of apprenticeship, this system is being challenged and may not suffice for training surgeons of the future. Costs, demands on time, patient safety, and increasing skill requirements are forcing surgeons to examine newer methods of learning to perform operations.

Aside from patient safety and ethical issues, there is support from the educational literature for training in a structured environment other than the OR. Creating this structured environment creates other issues related to resources and time constraints for busy surgeons. Computer-based skills training will provide the answer to some of these issues. The present cost, limited computing power, and lack of validation hamper the rapid incorporation of these tools into surgical residencies and training centers.29 It is expected, however, that computing power will continue to become faster and cheaper, thus leading to the development of powerful and cost-effective teaching tools in the near future.

Training surgeons will always require real patients and thoughtful mentors to learn to be intelligent and caring surgeons. Technical proficiency is only a single component in the mix, but it is an essential component. As computers continue to play larger roles in our everyday lives, so too shall they in surgical education.

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