

Innovations in surgery simulation: a review of past, current and future techniques

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Abstract: As a result of recent work-hours limitations and concerns for patient safety, innovations in extraclinical surgical simulation have become a desired part of residency education. Current simulation models, including cadaveric, animal, bench-top, virtual reality (VR) and robotic simulators are increasingly used in surgical training programs. Advances in telesurgery, three-dimensional (3D) printing, and the incorporation of patient-specific anatomy are paving the way for simulators to become integral components of medical training in the future. Evidence from the literature highlights the benefits of including simulations in surgical training; skills acquired through simulations translate into improvements in operating room performance. Moreover, simulations are rapidly incorporating new medical technologies and offer increasingly high-fidelity recreations of procedures. As a result, both novice and expert surgeons are able to benefit from their use. As dedicated, structured curricula are developed that incorporate simulations into daily resident training, simulated surgeries will strengthen the surgeon's skill set, decrease hospital costs, and improve patient outcomes.

Keywords: Surgical simulator; surgical training; virtual reality (VR); three-dimensional printing (3D printing)

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Introduction

Due to changes occurring in healthcare systems around the world, there has been an increasing demand for surgical training outside of the operating room. The regulations passed by the ACGME in 2003 have restricted the number of hour surgical trainees in the United States can work, requiring that new surgeons become proficient in a shortened period of time (1). Additionally, the high cost of operating room space coupled with decreasing reimbursements have further limited operating room-based training. Thus, there have been pressures to develop more efficient models of surgical training than the traditional apprenticeship design of surgical residency programs. Moreover, increasing emphasis on patient safety has further

limited the training experience of novice surgeons in the operating room, necessitating the development of training strategies that do not involve actual patients. Due to these pressures, there has been an increasing use of simulators in modern surgical training.

A simulator is a device or model used for training individuals by imitating situations they will encounter in real life (2). Surgical simulators, such as human cadavers, live animals, bench-top models and virtual reality (VR) systems recreate surgical situations for trainees to practice and hone their skills. When working with simulators, trainees can repeatedly practice techniques and manage complications until they achieve expertise in performing the simulated operation. As a result, surgical simulations aid in the development of critical psychomotor, technical

and judgment skills (3). Importantly, surgical simulation promotes repeated practice in a setting that forgives failure, and thus provides the opportunity to learn from one's errors without causing major harm. The implication is that repetitive use of surgical simulations will reduce operative times, lower complication rates and improve patient outcomes (4).

In recent years, a large number of surgical simulators have emerged that are unique to different surgical specialties, procedures and procedural variations. For example, different bench-top and VR simulators exist for the practice of endoscopic foreign body removal, laparoscopic common bile duct exploration, cleft palate repair and intestinal anastomosis among many others (5-7). Specific simulators also exist for unique complications of a specific surgery, such as a recently developed sheep-based simulator for managing vascular emergencies during skull base surgery (2). Finally, with the ability to practice surgeries on human cadavers and animal models, nearly any surgery can be simulated outside of the operating room.

In this review, we will discuss the history of surgical simulation, the types and benefits of simulators currently available to surgical educators, and finally the expanding role of surgical simulators in the future.

History of surgical simulation

Surgical simulators originated over 2,500 years ago, when they were first utilized to plan innovative procedures while maintaining patient safety. One of the first recorded instances of surgical simulation was the use of leaf and clay models in India around 600 B.C. to conceptualize nasal reconstruction with a forehead flap (8,9). Other examples of early simulator use for surgical training involved the use of wooden bench-top models, live animals and human cadavers (10). Ambroise Paré [1510–1590], considered one of the fathers of surgery, was known to take embalmed cadavers home to practice new surgical techniques (11). By practicing on both live and inanimate models, surgeons throughout history were able to pioneer new surgical techniques and practice operations without sacrificing patient safety.

The next great advancement in medical simulation did not occur until the 1980s, when computerized patient simulators (manikins) became integrals part of anesthesia training. The first commercially successful manikins, named Comprehensive Anesthesia Simulation Environment (CASE), were developed for training and assessing physicians' skills in anesthesia and critical care.

These original manikins used microprocessor chips and computer software to create artificial vital signs which responded to interventions, emergencies, and other factors. The success of the CASE series in anesthesia training led to the establishment of the first educational center dedicated to medical simulation on these manikins, the Boston Anesthesia Simulation Center (12). Since then, manikins utilizing wireless technologies, high-fidelity human likeness and computer images have been developed to enable training of a large variety of surgical procedures with remarkable realism (5).

The innovation with the highest potential for expanding the field of surgical simulation came with the introduction of VR simulation in the 1990s. VR simulations are computer-based systems which allow practice of surgical techniques on a computer; the surgical trainee uses tools to manipulate a series of computerized images, thus performing surgery in a virtual environment. The first VR simulators included a virtual Achilles' tendon repair, cholecystectomy, wound debridement and suturing (5,13,14). Unlike previous simulation models, VR simulators were safe, ethical and repeatable. Over time, extensive clinical research on VR simulators and the integration of new technologies have resulted in the development of increasingly effective and versatile models. For example, the Minimally Invasive Surgery Trainer Virtual Reality (MIST-VR) and other VR simulators for laparoscopic surgeries have been shown to improve performance in the operating room (15,16). Today, VR simulators combine actual surgical tools used in the operating room with extremely realistic computerized images. These "hybrid simulators" mimic entire operations with high fidelity (17).

More recent developments in surgical simulation have involved the creation of simulation programs for the robot-assisted surgical system, da Vinci. For example, the Robotic Surgical Simulator (RoSS) is a stand-alone device that teaches novice surgeons the skills required for performing robot-assisted surgery (RAS) (18). Additionally, simulation software can be directly loaded onto the da Vinci to allow direct surgical practice (5). As RAS becomes more prevalent, we will likely see the emergence of additional training simulators for the da Vinci.

Current simulation models

Low- vs. high-fidelity

Surgical simulation models can be low- or high-fidelity,

reflecting the closeness of the model to reality (19). Low-fidelity models only allow practice of individual skills or techniques rather than an entire operation, while high-fidelity models can replicate an entire surgery with a high degree of realism. Although high-fidelity models are desirable for closely emulating the operating room environment, low-fidelity models are cheaper and allow quick and repetitive simulation of a specific skill to enable mastery of individual techniques (20). Importantly, the level of fidelity should be appropriate to the type of task and training stage: a low-fidelity simulator is better suited for a novice practicing basic surgical skills such as hand-eye coordination and knot-tying, while a higher-fidelity system that encompasses a wide variety of skills better serves advanced surgeons (19). Within a single category of simulators, both low- and high-fidelity models exist. The following is a list of some of the most popular types of surgical simulators in use today.

Live animals

Operations on live animals are an effective form of surgical simulation because they share many of the same features as human surgeries. Successful surgery on an anesthetized animal requires adequate control of hemostatic systems, thus replicating human surgery with high-fidelity (17). As a result, resident surgeons working on live animals can practice every element of an operation, including not only the technical skills involved in a procedure, but the avoidance of complications and their management when they arise. Moreover, since operating on live animals closely emulates the actual operative setting, working with these simulators also allows multiple resident physicians to practice the communication and teamwork essential in the operating room (17,21). Because of the numerous benefits to working with live animals, *in vivo* porcine and canine models have been used extensively in endoscopic, laparoscopic and other forms of training, including endoscopic submucosal dissection, cholecystectomy and coronary bypass (17,22). Many studies have been conducted on the efficacy of these forms of training, and most have validated their use in improving technical skills and self-confidence (22-24). *Ex vivo* animal tissue is also sometimes used in surgical training, but offers lower-fidelity simulation than live animals. Oftentimes, animal tissue is combined with bench-top synthetic models to create a high-fidelity simulator (2).

There are drawbacks to the use of animals in surgical

training. For one, there are structural differences between human and animal anatomy. Additionally, some ethical concerns have arisen over the use of animals as surgical simulators. In fact, the UK prohibits the use of live animals for surgical simulation (17). Finally, using live animals for surgical simulation is expensive and requires multiple residents and faculty working together in order to monitor hemostatic changes.

Cadavers

Fresh cadaveric tissue is the gold standard for surgical simulation because of its approximation to living tissue (25). Unlike animal models, cadavers correctly simulate the actual anatomic structures encountered in the operating room. Although this form of simulation uses dead tissue and thus cannot faithfully emulate all physiological conditions, some cadaveric surgical courses have utilized pressurized systems to perfuse cadaveric tissues with blood. Perfusing cadaveric tissue creates high-fidelity models for vascular, microvascular and trauma surgery (25-28). Additionally, cadavers have been used for training flap coverage techniques as well as various endoscopic and laparoscopic operations (29,30).

However, embalmed cadavers have poor tissue compliance that makes some surgeries difficult (31). Human cadavers are also expensive, and their limited availability restricts their widespread distribution and use (32). Additionally, cadavers require regular maintenance and special facilities, and are not reusable following certain procedures. Therefore, it is important to determine the circumstances in which cadaveric training is superior to other methods of simulation in order to ensure that resources are appropriately allocated. For example, the incorporation of cadavers into a plastic surgery residency program and an arthroplasty course was found to increase participating surgeons' confidence (33,34).

Bench-top and laparoscopic box simulators

Bench-top simulators are synthetic stand-alone simulation models that allow practice and assessment of surgical skills. Common techniques offered by low-fidelity bench-top simulators include knot-tying and suturing (20). However, high-fidelity bench-top simulators which combine both synthetic and animal parts have also been developed (2). These complex models have been designed to replicate and train complete operations, such as fracture fixation, joint replacement and aneurysm repair (20). Because bench-top

simulators are effective and simple, they are commonly used by educators to assess the proficiency of novice surgeons.

Stand-alone simulators have also been developed for minimally invasive surgeries. Laparoscopic box simulators require the training surgeon to operate within a closed environment containing cameras that allow trainees to watch their own movements. One of the most common and simple laparoscopic box simulators, the McGill Inanimate System for Training and Evaluation of Laparoscopic Skills (MISTELS), consists of basic laparoscopic skills tasks including peg transfer, cutting, placing a ligating loop and suturing (35). With the advent of three-dimensional (3D) printing, high-fidelity laparoscopic simulators can accurately recreate complicated procedures under realistic condition (6). For example, 3D printing technology has been incorporated into hyper-realistic training models for laparoscopic pyeloplasty, thoracoscopic esophageal atresia repair and other minimally invasive surgeries (6,36). Recently, 3D printing has been used to create patient-specific models for preoperative planning of complicated procedures (37).

The efficacy of bench-top and laparoscopic box simulators in improving surgical skills has been validated by multiple studies (32,38-41). Observed benefits from using these simulators include the development of hand-eye coordination and dexterity in performing surgical tasks. Thus, a curriculum created by Scott *et al.* utilizing this technology in surgical residency training was found to successfully teach surgical skills in a cost-effective manner (40,41). Additionally, the benefits of MISTELS in laparoscopic training are well-established, leading to its use in many surgical training programs (35).

The downside of these simulators is that while high-fidelity models can replicate complete operations, they are expensive and less readily available. Low-fidelity simulators, meanwhile, only teach basic surgical skills. Moreover, both low- and high-fidelity bench/laparoscopic box simulators incorporate synthetic materials, limiting the degree of realism they are able to achieve compared with cadaveric and animal simulators.

VR simulators

VR surgical trainers allow the user to develop hand-eye coordination, fine motor skills and familiarity with a procedure through the use of surgical tools that manipulate a virtual environment. Due to the increasing processing power and graphical capabilities of computers, modern VR

simulators create realistic environments that capture minute anatomical details with high accuracy (42). Therefore, modern VR simulators offer high-fidelity and anatomically correct simulations that are entirely reusable. Additionally, because VR simulators are computer-based, surgical trainees may practice a variety of different simulations on a single unit. For example, the NeuroTouch VR neurosurgery simulator enables simulation of microdissections, tumor aspiration, debulking and hemostasis (43).

One of the most attractive features of VR simulation is the ability of these systems to offer real-time haptic feedback to users about their performance within the simulation. Common metrics produced by VR simulators include time to complete a task, errors made during surgery, and the surgeon's economy of movements (5). These metrics provide a method for skills evaluation that is objective and quantitative. Therefore, VR simulators offer a direct advantage over other simulators by letting trainees practice repeatedly, without supervision, while receiving direct feedback from the simulator itself. Additionally, the haptic metrics produced by VR simulators enable educators to assess the proficiency of novice surgeons and monitor their improvement (44).

Most VR simulators are designed to teach laparoscopic and endoscopic procedures (35), as their reliance on video monitoring makes them naturally suited to the VR platform. Both low-fidelity simulators ("Task Trainers") teaching basic surgical procedures and high-fidelity models of complete operations are commonly used. For instance, the MIST-VR system is a low-fidelity system designed to teach basic laparoscopic skills, suturing and knot-tying (45). High-fidelity VR systems include the LapSim, Lap Mentor, and NeuroTouch. The Lap Mentor is a particularly inclusive system that includes over 65 cases in the fields of general surgery, gynecology, urology, and bariatric surgery (46).

There is substantial evidence supporting the use of VR simulators in surgical training (15,16). VR simulation has been found to reduce operative time and to improve the performance of surgical trainees (16). Additionally, performance metrics produced by VR simulators have been shown to strongly correlate with operating room performance (47,48). Drawbacks of VR simulations include high costs, lack of force-feedback, and limited realism of some simulation models (49). However, as VR technology advances, simulators are becoming more cost-effective and better able to replicate human anatomy. Because of the versatility of VR systems and the evidence for their efficacy in improving operative performance, it has been

recommended that these simulators be formally included in surgical curricula (4,17).

RAS simulators

Robot-assisted laparoscopic surgery (RAS) simulators represent a relatively new development in the field of surgical simulation. The da Vinci surgical system, first introduced in the United States in 1999, involves a surgeon using foot pedals, dual hand controls and a controllable 3D camera to guide a robot through surgical procedures (50). The da Vinci system's design makes it naturally suited for VR simulation; with the use of a simulator, the surgeon views a virtual environment rather than a live endoscopic feed through the user interface. As a result, several simulators have been designed to train surgeons in using the da Vinci.

Currently, there are 4 widely used RAS simulators for the da Vinci System: the SEP-Robot, RoSS, dV-Trainer, and the da Vinci Skills Simulator (50). The da Vinci Skills Simulator is a hardware pack which loads a VR simulator onto the actual da Vinci device (51). The RoSS and dV-Trainer, on the other hand, are stand-alone devices with controls resembling those of the da Vinci system (50). These simulators are low-fidelity and thus only allow practice of individual surgical tasks testing hand-eye coordination, tissue manipulation, suturing and knot tying (52). Like other VR simulators, the da Vinci simulators also produce metrics of performance based on completion time, error measures, and motion analysis (50). Because of their ease-of-use and readily available metrics, these simulators are becoming increasingly used for training novice surgeons in RAS.

Validity studies on the use of RAS simulators suggest that they accelerate the initial console training for surgeons (50). Some studies suggest that the da Vinci Skills simulator could be a valuable tool for assessment of RAS technical skills and credentialing of RAS surgeons (51). However, the available da Vinci simulators have been criticized for their high costs and lack of high-fidelity surgical simulations (50). The development of simulators for RAS is still in its infancy, so it is likely that cheaper and more sophisticated systems will be available in the future. Moreover, additional studies are still necessary to confirm whether skills gained from RAS simulators translate to use of the da Vinci (53).

Innovations in surgical simulation and simulators of the future

Traditional surgical simulations have involved practicing

common procedures and tasks that are likely to be encountered in the operating room. Simulators that train simple hand-eye coordination skills, knot-tying and suturing have wide utility because these operations are frequently performed. However, modern advances in technology have enabled the development of surgical simulators that replicate complex surgeries unique to the anatomical variations and disease states of actual patients (54). These patient-specific surgical simulators achieve the highest level of fidelity by allowing surgeons to practice the specific case they will be performing on models that accurately represent their patient. Additionally, augmented reality combined with wireless technologies are making telesurgery a legitimate tool for expert surgeons to assist novice surgeons in complex operations. Therefore, recent innovations in surgical simulation are focused on improving surgical outcomes, either by increasing the operating expertise of the operating surgeon (rapid prototyping and patient-specific VR) or increasing access to expert surgeons (telesurgery).

3D rapid prototyping

3D rapid prototyping involves using medical imaging, including CT and MRI, to create patient-specific 3D models that enable the planning of various operations. Multiple technologies are currently being used to build synthetic models of patient-specific organs and vasculature. These technologies include fused filament deposit, stereolithography, scintigraphy and 3D printers (54). Some newly developed multimaterial 3D printers can produce models with multiple tissue types. As a result, some of the models produced by rapid prototyping are able to replicate actual patients' anatomical structures with remarkable realism (37,54-57).

Some of the most pioneering work in rapid prototyping is occurring in the field of neurosurgical simulation, where 3D printers are used to create reliable models of patient-specific cerebrovascular pathology from information provided by CT angiograms. When printed with the surrounding bony structures, these models allow the surgeon to plan the trajectory of approach to aneurysms and to test different aneurysm clips for the appropriate size and shape (54,55). Additionally, rapid prototyping has been used in cardiac surgery, where 3D-printed heart models rendered from cross-sectional patient images have been used in simulations to train staff on postoperative critical care (56).

Many studies have shown the benefit of using 3D printing preoperatively. One study found a strong

correlation between 3D-printed models and the actual patients' anatomy (57). Additionally, studies have shown that surgeons using these models find them easy to use and superior to the use of traditional imaging alone (54,58). With further evidence supporting the benefits and accuracy of rapid prototyping, it is possible that 3D models will one day be routinely printed to plan procedures and improve patient outcomes.

Patient-specific VR simulator

VR surgical simulations using patient imaging data represent another effective way to practice a procedure preoperatively. While many surgeons simulate procedures mentally before entering the operating room, mental simulation does not allow for information sharing between team members and might unintentionally exclude important details. Anatomically accurate VR simulations with patient-specific anatomy eliminate the risk of human error and allow visual communication of the surgical plan not just with team members, but with the patients themselves (59).

Patient-specific simulators have recently emerged for use in pancreatectomies, hepatectomies, renal surgery and hand surgery (59-61). In one renal surgery simulator, patient CT data is captured and reproduced on a 3D virtual simulator (61). This allows the surgeon to practice laparoscopic procedures preoperatively in a virtual environment with accurate renditions of the patient's anatomical variations. The overall accuracy of the simulator is high, capturing structures such as tumors, ureters, and renal arteries and veins with 95–100% accuracy (61). The time needed to generate these simulations is relatively short, taking around 2.5 h for the hepatectomy and pancreatectomy simulators (59). Therefore, these technologies may be effective tools for preoperative planning of complicated procedures. Unlike 3D printers, these simulators are also readily reusable and do not consume resources, further supporting their clinical utility. However, patient-specific VR simulators are a new technology and thus need additional studies validate them.

Virtual interactive presence and augmented reality (VIPAR)

With increasing resolution of cameras, higher speeds of internet connectivity and the introduction of augmented reality, newer technologies are now allowing surgeons to collaborate remotely. One such system for remote surgical cooperation is VIPAR (62). Through this system,

the visual field of a surgeon in one location is converted into a simulation that is projected to a surgeon elsewhere. As a result, the operating surgeon can be guided in real-time by a more experienced surgeon. The VIPAR system utilizes augmented reality technology to enable audiovisual collaboration over the internet with just a 760 ms delay (63). As a result, participants at different locations may collaborate to identify anatomical structures, guide surgical maneuvers, and discuss overall surgical approach.

The clinical use of VIPAR has been validated in numerous studies. For example, VIPAR has been used in orthopedic surgery for training residents with an attending surgeon immediately available in an adjoining room. This practice, known as telementoring, was rated positively by the surgeons utilizing the VIPAR system (64). Additionally, VIPAR has been shown to be feasible for long-distance telecollaboration in neurosurgical studies on cadavers (64). Finally, the system is highly affordable, costing just \$15,000 for 1 year of use (65). Because of its low cost and clinical applicability, VIPAR represents one potential way to improve collaboration and facilitate training.

Discussion

Surgical simulation has undergone an enormous transformation since the early 1990s, evolving from manikins and plastic bench-top kits to 3D printing and patient-specific VR systems. This evolution of surgical simulation has paralleled the evolution of technology in general, such that currently used models are increasingly relying on VR, customization, and internet connectivity much like advancements in mobile applications and gaming. Therefore, surgical simulators today are more collaborative, realistic, and versatile than in the past.

The recent evolution of technologically innovative simulators has seen the development of tools that are useful to both expert and novice surgeons. While traditional simulators like cadavers and bench-top models were mostly used to train and assess the skills of novice surgeons, new-age simulators help expert surgeons prepare for unique surgical conditions specific to the patient. These new devices are redefining the role of simulations, expanding their use from training to preoperative planning. The development of new-age simulators is thus in line with the rise of precision medicine, individualizing surgical preparation to the patient's unique qualities.

Despite recent advances, traditional surgical simulation models readily available to medical institutions, such as

bench-top models, cadavers and laparoscopic trainers, can still effectively train surgeons and improve operating room performance. For example, multiple meta-analyses have determined that the addition of simulation to conventional surgical training results in improved surgical performance, reduced surgery times, decreased error rate and improved patient outcomes (66-68). Other clinical trials focusing on VR simulators of laparoscopic surgery have similarly validated that the use of these systems reduced surgical complication rates, improved the development of trainee surgical skills and shortened operative times overall (69-71). Essentially every form of surgical simulation previously discussed, from animal models and cadavers to robotic trainers and 3D-printed models, has demonstrated some benefit to surgical training programs (15,16,22-24,32-35, 38-41,47,48,51,54,58,64). Moreover, many simulators have shown to be cost-effective options for training residents (72). Thus, they represent viable options for surgical training programs.

There is now a need to incorporate these simulators into structured surgical training curricula. While many surgical workshops are organized annually to teach specific surgical procedures on simulators, the presence of longitudinal courses incorporating simulators is lacking. It is only with consistent use, and objective methods of assessment, that programs can maximize the utility of simulation (3). Four conditions should be met in a curriculum utilizing surgical simulators in order to maximize their utility, including mandatory participation, proficiency-based training, distributed training schedule, and overtraining (4). As dedicated, structured curricula are developed that incorporate simulations into daily resident training, simulated surgeries should strengthen the surgeon's skillset, decrease hospital costs and improve patient outcomes.

Conclusions

The revolution in surgical training, brought about by limitations in work hours and concerns for patient safety, has resulted in extraordinary innovations in simulation. However, it has also brought on new changes in surgical training. Accountability for the efficacy of surgical training has required educators to be methodical about verifying that standard training is effective, and that simulation can actually improve trainees' abilities to care for patients. Whether surgical simulation is actually improving the efficiency of skills acquisition is truly unknown; more reliable methods of measuring skill acquisition will be

required for this process. At this point, educators will be challenged by how, where, when, which, and how often simulations should be used in clinical training. As the simulators improve, and the measurement of skills acquisition improves, we will likely find a way to maximize skill acquisition for physicians in training. This will hopefully decrease the cost of physician training while increasing physician quality in the future.

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Footnote

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