NARRATIVE REVIEW

Past, present, and future of surgical simulation and perspective of a developing country: A narrative review

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Abstract

Healthcare systems around the globe have been revolutionised in the last few decades, resulting in a greater need and demand for surgical education outside the operation theatres. Surgical education through simulations started around 2,500 years ago when they were first used in the planning of unique and innovative surgeries while ensuring the safety of the subjects. Currently, simulations include animal models, cadaveric models, benchtop models and complex robotic models. In a programme involving surgical simulators, four requirements are followed to optimise their effectiveness, including mandatory involvement, skill-based instruction, standardised training plan, and overtraining. We can make a reasonable estimation that the future is technology-based. The speed with which we anticipate the fusion of these virtual reality and robotics-based simulation technology with medical educations and practices largely depends on the affordability and economics of these tools. The current narrative review was planned to highlight the historical aspects of simulations, their role in surgical education, and their importance in the future as an essential adjunct to surgical education.

Keywords: Benchtop simulation, Surgical education, Virtual reality.

DOI: https://doi.org/10.47391/JPMA.01-1046

Introduction

Healthcare systems around the globe have been revolutionised in the last few decades and it has resulted in a greater need and demand for surgical education outside the operation theatres (OTs). In countries like the United States and the United Kingdom, there have been fixed work-hours for the residents, resulting in a fewer OT procedures for them when they have to acquire skills for advancement in their field.[1] Also, the increasing costs of OTs and burden on the economy of the hospitals have resulted in surgeons being more cautious than ever before. Therefore, there is already enough pressure on the surgical training programmes to equip themselves with unique and effective models for surgical education, away from the old traditional method of surgical training in which apprenticeship was considered essential and effective. Patient safety is also a consideration. The residents who are in their surgical infancy have the least exposure with actual patients. Due to all these limitations, modern surgical education has encouraged the trend of simulations.

A simulator is a gadget that can reciprocate real-life scenarios and it can help the residents to practise a procedure or a skill over and over again.[2] There are various kinds of surgical simulations, like animal specimens, human cadavers, benchtop models and virtual reality (VR) models, and they help students and residents to learn as well as polish their skills by performing the same thing again and again until they master the skills and learn to manage the complications while learning it. While doing so, they learn and develop cognitive and psychomotor skills and pictoral memory that can be applied in real-life surgery.[3] Another important advantage is that mistakes and failures during simulations can be forgiven and they can make one's learning much better without causing any major danger. It is implied that enough practice on simulations can make learning of the new skills better, fast and this can help in reducing the actual operating times as well as a better judgment which can eventually lead to better patient outcomes.[4]

Lately, surgical simulators have emerged that are unique regarding different specialties, various procedures, and even variations in the same procedures. For example, removal of foreign bodies from gastrointestinal track (GIT) and airways, common bile duct exploration by laparoscopy, repair of cleft palate and anastomosis of intestines, and many other procedures are practised over benchtop and VR simulators. There are some specific simulators on which specific emergencies can be practised, like sheep-based simulation gadgets have been developed where vascular emergency management can be practised.[2] Another aspect of the simulations on animals, cadaveric, or mechanical models is that they

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enable the surgeons to practise almost any kind of surgery outside the OTs.

History and development of simulation training: Surgical education through simulations started around 2,500 years ago when they were first used in the planning of unique and innovative surgeries while ensuring the safety of the subjects.[5] The foremost example of the surgical simulation was the nasal reconstruction with the help of a forehead flap conceptualisation while using the leaf and clay specimen models as simulators.[6] Other different simulations in the early era were benchtop models of wood, human cadavers and animal specimens.[7] Ambroise Pare was known to keep embalmed cadavers at his house where he would practise new surgical procedures and techniques.[7]

Although the trend of simulations was set over many millenniums ago, further progress in the field did not happen until the 1998s when anaesthesia training included mechanical patient simulations. First-ever commercially produced manikins were named Comprehensive Anaesthesia Simulation Environment (CASE) and they were used to train and assess the skills of physicians in anaesthesia as well as in critical care.[8] These original manikins employed different computer software along with microprocessor chips which created artificial signals to respond to emergencies and other factors. This became so popular and successful that they established a dedicated medical centre to teach by simulations, called the Boston Anaesthesia Simulation Centre.[9] After that, there have been many modern modifications in the manikins, like wireless technology, high-resolution images that have enabled the trainees to perform the surgical procedures at a large scale and with a remarkable realism.[10]

VR-based simulations are computer systems that allow the trainees to perform surgeries in a virtual environment and the trainees can manipulate computerised images and tools to practice over it. VR-based simulators were first employed during the 1990s in many procedures, like cholecystectomy, wound suturing and Achille's tendon repair.[10-12]

With time, modern research on VR-based simulators and integration of other technologies resulted in other innovative technologies, like the Minimally Invasive Surgery Trainer Virtual Reality (MIST-VR) and various VR-based systems over which laparoscopic surgical practice and performance improvement can be done.[13] Nowadays VR-based simulators employ actual surgical instruments combined with high-resolution images. These are called "hybrid simulators" and they can mimic the entire surgery with high precision.[14]

The next phase of developments in the field of the surgical simulation comprised robot-based surgical systems, like da Vinci. The Robotic Surgical Simulator (RoSS) is an isolated device that can help inexperienced surgeons to develop and practise the skills of robot-assisted surgery (RAS).[15] It is expected that with the increasing popularity of RAS, additional simulational training on da Vinci will also increase.

Depending on the similarity to the reality, surgical simulation models are called either low-fidelity or high-fidelity.[16] Some of the most commonly used simulators are:

Live animals: Surgeries performed on live animals mimic real-life surgeries as they share many anatomical features with human beings. Performing surgery on live animals under anaesthesia requires the normal haemostatic systems of the body and it can be called a high-fidelity surgery simulation. This not only helps the surgeon to perform a surgery with high fidelity, but also helps in mastering a skill avoiding the complications and their management. It also helps collective teamwork and communication as multiple surgeons, and other team members can perform surgery at the same time.

Due to these and other benefits, live animals, like pigs and canines, have been used for simulations of endoscopic resections, cholecystectomies, and other laparoscopic techniques and coronary bypass surgeries. The use of live animals for these procedures in surgical education has been studied and proved by many studies.[17-20]

Sometimes some parts of these animals are taken out of the body and different techniques can be practised and mastered over either directly or by making benchtop models.

There are many reasons for using these animals in surgical education. The first being that there are some basic structural differences among the anatomical and physiological features of human beings and animals.

Second, there are ethical considerations that have limited their use as surgical simulators. In the UK, there is the prohibition of using live animals as surgical simulators.[14]

In addition to the aforementioned drawbacks, these live animal models are very expensive to design and maintain as it takes a lot of resources and manpower to manage the whole surgical procedures.

Cadaveric simulators: Fresh cadavers are perfect candidates for simulation as the tissue has not gone bad and it is close to the living tissue.[21] Compared to the animal models, these cadaveric simulation models are better at reciprocating the actual human anatomy as we encounter in OTs. On the other hand, these simulators might not be the ideal as far as physiological homeostasis is concerned. Some cadaveric surgical simulation courses employ perfused cadavers that are pressurised and can be used for vascular procedures.[21] Other procedures that are practised over the cadaveric models are endoscopic, flap coverage and laparoscopic techniques.[22]

Cadaveric models have poor tissue strength and they can make any procedure difficult. Also, their supply is limited and they require special maintenance and cannot be reusable for a procedure.[23] So it is necessary to define which procedures can be practised best over cadaveric models, like their use in the plastic surgical education and joint surgeries have been proved very fruitful.[24]

Bench-top and laparoscopically box-oriented simulators: These benchtop laparoscopically box-oriented simulators are relatively complex simulation models that are used to practice and imitate high-fidelity procedures, like aneurysm repairs and joint-related surgeries. These models are very easily available and they are used very commonly in surgical education for the training of beginners in surgery.

Stand-alone simulation models are most commonly used for minimally invasive surgeries where they allow the novice surgeons to control their movements with the ports. The simplest of these models where tasks, like peg transfer, tissue cutting, and dissection, suturing and placing a loop on a pole, are performed and practiced is known as McGill Inanimate System for Training and Evaluation of Laparoscopic Skills (MISTELS).[25]

High-fidelity laparoscopic simulation models can reliably replicate complex procedures under practical conditions with the discovery of three-dimensional (3D) printing. For example, 3D orienting technology for laparoscopic pyeloplasty, video-assisted thoracoscopic surgery, assisted oesophageal surgeries, and other various complex laparoscopic procedures have been integrated into hyper-realistic training models. Three-dimensional printing has increasingly been used to construct patient-specific templates for complex operations and pre-operative preparation.[26]

Therefore, a textbook using this technology in surgical residency training was found to teach surgical skills in an efficient cost-effective manner.[27] Besides, MISTELS's advantages in laparoscopic training are well known, which contribute to its use in many surgical training programmes.[28]

Such simulators 'drawback is that although high-fidelity prototypes will simulate full functions, they are costly and far less accessible. Furthermore, low-fidelity simulators demonstrate only simple surgical skills. Besides, both low- and high-fidelity bench/laparoscopic box prototypes incorporate synthetic materials that limit the level of complexity they can accomplish relatively well to the corpse and animal-based simulators.

VR simulators: Using surgical devices that leverage a simulated world, VR surgical trainers allow the patient to improve hand-eye coordination, fine motor skills, and experience with a procedure. Modern VR simulators build realistic worlds that capture minute anatomical details with high precision due to the growing computing power and graphical capabilities of the computers.[29]

Current VR simulators also deliver high-fidelity and anatomically accurate models, which can be fully reused. Furthermore, as VR simulators are computer-based, surgical trainees conduct multiple simulations on a single device. The NeuroTouch VR neurosurgical simulator allows for the application of delicate procedures, like haemostasis, microdissections, tumour aspiration, and tumour debulking.[30]

One of VR simulation's most enticing characteristics is the potential of these devices to give the users real-time haptic feedback on their success inside the simulation. Common metrics created by VR simulators include time to complete a mission, mistakes made during surgery, and the efficiency of the movement of the surgeons.[10]

These indicators have an unbiased and authentic basis for measuring abilities. VR simulators thus provide a distinct benefit over other simulators by encouraging trainees to learn over and over again, without interference, getting direct input from the simulator itself.[31]

Most VR simulators are equipped to teach laparoscopic and endoscopic procedures since they are suited to the VR framework by their dependence on video monitoring.[32] Both low-fidelity systems ("Task Trainers") are widely used to teach simple surgical techniques and high-fidelity versions of full operations.[25]

The MIST-VR system, for example, is a low-fidelity device intended to teach simple laparoscopic techniques, suturing and knot tying. The LapSim, Lap Coach, and NeuroTouch are high-performance VR devices. The Lap Trainer is a highly comprehensive programme, including more than 65 cases in general surgery, gynaecology, urology, and weight-loss surgeries.

The usage of VR simulators in surgical education is backed by significant data.[33] VR simulation was found to minimise operating time and boost surgical trainee efficiency. Besides, performance indicators provided by VR simulators have shown to correspond closely with the output in OTs.[34]

VR simulations' disadvantages include high prices, lack of force input, and minimal realism in certain simulation models. But, as VR technology progresses, simulators are getting increasingly cost-effective and more capable of replicating human anatomy. Due to the extreme simplicity of VR devices and the proof of their effectiveness in enhancing operational efficiency, it was proposed that such simulators be used officially in surgical courses.[35]

Robot-assisted surgery (RAS): Simulators for RAS represent a fairly recent advancement in the area of clinical simulation. The robotic surgical training models, first adopted in the United States in 1999, require a surgeon utilising foot pedals, dual-hand levers, and a tunable 3D lens to direct a robot during surgical interventions.[36] The architecture of the da Vinci device renders it inherently ideal for VR simulation; via the software, the surgeon experiences a simulated world rather than a live endoscopic display, utilising a simulator. Consequently, many simulators were built to educate surgeons using da Vinci.

The da Vinci device has 4 commonly deployed RAS simulators: the SurgicalSim Educational Platform (SEP)-Robot, the RoSS, and the dV-Trainer. The Robotic surgical training models is a hardware kit loading a VR simulator into the da Vinci system itself. On the other side, the RoSS and dV-Trainer are stand-alone apps that have controls identical to those of the da Vinci programme.[36] Such simulators are low-fidelity and thus require only the learning of individual surgical tasks that measure hand-eye coordination, tissue handling, suturing and knot tying. As with other VR simulators, the da Vinci simulators often provide output indicators dependent on completion period, error measurements and movement analysis.

Validity research on the use of RAS simulators indicates that initial console preparation for surgeons should be improved.[37] Some studies have suggested that the da Vinci Abilities simulator could be a valuable resource for testing RAS technical skills and RAS surgical qualifications.[38-40]

The current robotic surgical training models have, however, been criticised for their high expense and lack of high-fidelity surgical simulations. The production of RAS simulators is still in its infancy, and simpler and more advanced solutions may be accessible in the future. Besides, more research is also required to validate whether skills learned from RAS simulators transfer into the da Vinci usage.

Discussion

Since the earlier 1990s, surgical modelling has experienced a massive transition from manicures and cardboard benchtop sets to 3D printing and patient-specific VR-systems.

This development of surgical simulation has largely mirrored the development of technology, so that commonly utilised models progressively depend on VR, automation, and internet access, just like developments in smartphones and gaming. But now, surgical simulators are more interactive, practical and flexible than they were in the past. Although conventional simulators, such as corpses and benchtop models have been mainly used to practise and test the abilities of inexperienced surgeons, new-age simulators enable experienced surgeons to plan for complex patient-specific surgical situations.

Despite recent developments, conventional training devices that are widely accessible to medical facilities, such as benchtop models, skeletons and laparoscopic coaches, will also successfully educate surgeons and enhance efficiency in OTs.

Several meta-analyses, for example, have concluded that incorporating simulation to traditional surgical training results in increased surgical efficiency, shortened operating times, diminished failure rate, and better clinical outcomes.[5,41]

Every previously explored method of surgical simulation, through animal models and corpses to robotic coaches and 3D-printed models, has provided some value to surgical education programmes. In comparison, other simulators provided cost-effective training opportunities, and they depict feasible alternatives for courses in surgical training.

Such simulators are also expected to be incorporated into the formal surgical training curricula. Although several surgical seminars are conducted annually to teach basic surgical techniques on simulators, there is a shortage of clinical courses that integrate simulators. In the UK, training programmes optimised the utility of simulation only with clear usage and unbiased methods of assessment.

In a programme involving surgical simulators, four requirements were followed to optimise their effectiveness, including mandatory involvement, skill-based instruction, standardised training plan, and overtraining.[42]

Training through surgical simulation in Pakistan, a developing country: Pakistan is among the developing countries of the world. Its population is expected to be beyond 220 million, making it the 5th largest population in the world. The healthcare system of Pakistan is considered below par compared to that of any developed country. The consequences of this imbalanced structure, on one hand, are inadequate healthcare provision to the patients and, on the other hand, a huge load on the hospitals, OTs, and healthcare staff

In Pakistan, a traditional supervisor/mentor-based training model makes surgical residents and trainees pass through different steps. They start observing and assisting the surgical procedures under the supervision of expert surgeons. They are supposed to develop fine and intricate operative skills as their training proceeds. It is mostly achieved through continuous devoted practice on patients.[43] Inexperienced residents polish their skills under the supervision of their mentors by learning more advanced and complex techniques. But now this learning procedure is losing its worth worldwide as it results in increased intra-operative complications, causing more medico-legal consequences.[44] Moreover, due to the enhanced burden on OTs and a larger number of surgical residents, many trainees do not get enough time and hands-on surgery, representing inefficient learning.

Simulators provide a safe environment for teaching any surgical technique to junior residents where they can learn and repeat any procedure under their mentor supervision, and mistakes and errors can be pointed out at any time during the procedure without any harm. The most commonly applied surgical simulation in Pakistan are laparoscopy simulators, box simulators, and VR simulators using a physics-based simulation, called Simulation Open Framework Architecture (SOFA).[45] These simulators are widely used in acquiring skills for minimally invasive surgery (MIS). MIS is the rapidly emergent field that is gradually replacing open surgery manoeuvres for its safety, less time-consuming, and few post-operative complications. One such simulator used for MIS is a virtual simulator which is a novel VR laparoscopic simulator enabling the surgeons to work on their skills outside OTs. It gives a real-time working experience to the operators through visual graphics to practise their instruments handling for camera navigation, dissection, clipping, grasping and hand-eye coordination. Another simulator, called Box Simulator, is mostly used by gynaecology residents. He Box Simulator is an opaque rectangular-shaped box that has a camera in the middle attached to the monitors. This camera also acts as a laparoscope. Other such simulators are human body-based models that assist residents in learning basic surgical procedures.

Simulation-based teaching to residents has shown good results in skills-building training.[46] It is therefore implied that this type of training and tele-mentoring is the future of surgical training, and demands more efforts and resources from the authorities concerned for its advancement in Pakistan. Simulators for open or major surgeries are not in great use in Pakistan yet. Also, there is a need to develop a centralised simulation centre that can be used for all the trainees in a developing country, like Pakistan, and get a certificate after going through its curriculum. These measures are not yet possible may be due to financial inadequacy and cost-effectiveness and poor response from a large number of public-sector institutions and their administrations.

Future of surgical simulation: As the surgical world is moving from open surgeries to MISs, the use of VR simulators has increased in training and learning procedures. VR uses an artificial graphical environment which gives its user a sense of realism and awareness which helps in the improvement of eye-hand movement coordination, spatial alignment orientation, and virtual tissue manipulations. In customary clinical practice, the use of VR simulators is restricted by limited graphical details and camera movements. Moreover, the user is aware of the artificial environment and computer-generated specimen. With recent progress in multimedia and gaming graphics technology, fine details are being created in tissue specimens with time and VR applications are now combined with head-mounted displays. By performing team training sessions in 360 camera interface immersion, the user's sense of awareness in surrounding reality is created which provides better results in training. In the future, VR simulators are expected to expand their standing beyond the scope of MIS. It has also shown immense promise as an imperative teaching tool in surgical training programmes all around the world.[47]

In the age of information, the paradigm of surgery is shifting from a traditional OT where 5-6 people on average are washed up and handle the instruments passively to a more sophisticated and equipped surgical compound where all instruments, supply chain, and data tracking is done by robots with artificial intelligence (AI).[38] From the patients' entrance into the OT to their discharge from the recovery room, there will be least human contact. All this drive and integration will be overlooked by a single person operating from a distant room using simulators.[48] This is regarded as the future of surgery[49]. The use of simulators has made its way into aviation and military technology.[49] In the future, it is anticipated that an injured soldier will be operated on a man-less air ambulance by a surgeon operating from thousands of miles away.[49]

Conclusion

Simulation-based training has proved to be a good assessment tool for evaluating the experience and aptness of trainees without endangering patients' safety. By integrating AI components with simulator programmes, an objective as well as subjective assessment can be done by focussing on trainee's knowledge, skills, timeliness and expertise. This has led to the integration of these simulators into the curriculum of trainees and students in various institutions. Warming up on simulators before going to the OT has shown better results as far as intra-operative errors are concerned.

Disclaimer: None.

Conflict of Interest: None.

Source of Funding: None.

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