3D Simulation and Modeling for Surgeon Education and Patient Engagement

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Anna Przedlacka, Przemyslaw Korzeniowski, Paris Tekkis, Fernando Bello, and Christos Kontovounisios

Surgical Education

Surgical training has evolved enormously in the last decades. Traditionally, it involved an apprentice-like model outlined by Halstead in the beginning of twentieth century [1]. It was based on a high-volume, hands-on training with a gradually decaying level of supervision, until the trainee was judged by the mentor competent enough to operate on their own. With time, the structure and the content of the educational material have become more defined, and detailed curricula have been developed. Regardless of the educational model, the aim of surgical training has always been focused on producing a highly skilled operator capable of performing independently at the safest possible level.

Due to the reduction in working hours and a substantial increase in knowledge and patient safety requirements, the traditional model of surgical education is no longer sustainable. The development of digital technologies has allowed an introduction of new methods of learning surgery, with an aim to utilize the reduced time more efficiently and effectively. A significant proportion of the surgical training have now moved outside of the traditional setting of the operating theatre into the skill and simulation labs. The question regarding the simulation training has shifted from *"Is it effective?"* to *"How can it be best embedded, supported and funded?"* [2].

Gaining core surgical skills on animals or cadavers is expensive and raises ethical concerns, thus restricting their use in everyday training [3]. Using inexpensive, low-fidelity task physical trainers can provide effective training of the key elements of the procedure, but this paradigm lacks (in most instances) the real-life effect of surgery. Moreover, animals and cadavers, as well as foam, silicon or plastic parts used in task trainers, lack the physiological behaviour and different biomechanical properties, compared to living human tissue. Hence, these methods do not provide sufficient realism. Finally, they require feedback from a tutor.

The rapid increase in computer power and emergence of haptic technology [4] resulted in an alternative approach – a computer-based simulation system enabling training on a virtual patient [5]. Such systems, often referred to as

A. Przedlacka
Department of Surgery and Cancer, Imperial College London – Chelsea and Westminster Hospital, London, UK

P. Korzeniowski
Department of Surgery and Cancer, Imperial College London, London, UK

P. Tekkis · C. Kontovounisios (✉)
Department of Surgery and Cancer, Imperial College London – Chelsea and Westminster and the Royal Marsden Campus, London, UK
e-mail: c.kontovounisios@imperial.ac.uk

F. Bello
Centre for Engagement and Simulation Science, Imperial College London, London, UK

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virtual reality (VR) simulators, typically consist of a 2D or 3D display, a computer running the simulation software and a physical human-computer interface device mimicking the surgical instruments.

The device tracks the manipulation of the instruments and often can recreate the sense of touch by providing force feedback to the user (a haptic device). The software is responsible for taking input from the input device, simulating the interactions between the instruments and the virtual anatomy, rendering the 3D image of the surgical site and, if supported, calculating the forces sent to the user via the haptic device. Additionally, the software can record, analyze and store user performance.

The advances in 3D technologies have added new advantages to the already established application of simulation technology. They have led to the development of environments and scenarios which are more complex and thus able to more closely resemble real operations. 3D modeling has a central, paramount role in this evolution – it produces models that can be used independently as a sophisticated depiction of the anatomy or form the basis for the 3D simulation tools. 3D printing, or additive printing technology, has broadened the surgical horizons even further. The physical 3D models are manufactured through layering of printing materials based on digital 3D models.

Hybrid simulation, which combines the advantages of a physical 3D printed model (haptic feedback, deformability) with advantages of a VR simulator (building complex interfaces and environments), is an especially exciting joint application of both technologies [6]. The inclusion of haptic feedback seems to be an important factor in the training on VR, and the lack of haptic feedback might prove the application of VR less successful than a standard black box simulator [7].

Since the 1990s, virtual reality (VR) simulators have been expected to become as important for surgery as flight simulators are for aviation [8]. In 2001, Satava stated that "*The greatest power of virtual reality is the ability to try and fail without consequence to animal or patient. It is only through failure – and learning the cause of failure – that the true pathway to success lies*" [9].

High-fidelity virtual reality simulators have several advantages over the traditional methods of surgical training. They offer a safe, controllable and configurable training environment free from ethical issues in which clinicians can repetitively practice their skills.

VR simulators improve patient safety – not only because patients are not at risk during actual training but also because surgeons trained on VR simulators show higher competencies [10, 11].

VR simulators improve the educational experience by providing a wide selection of training scenarios diversified in terms of virtual patient's anatomy and pathologies. This overcomes the problem of waiting for a suitable real-life case and allows for controlled clinical exposure, where trainees start with basic cases moving gradually to more complex ones when they feel confident to do so.

Training on VR simulators does not require the presence of a supervising expert. By analyzing user performance in real-time, simulators can give immediate feedback during the procedure, which is crucial for efficient training [12]. The formative and summative assessment at the end of each training session helps to track user's learning progress that may be used in the future for credentialing and certification [13].

VR simulators have low maintenance costs and, except for calibration, practically require no preparation before or during the training session. Students and delegate surgeons can train on their own, whenever the equipment is available. They are reusable allowing for repetitive training of the same procedure countless times without incurring additional costs.

Experts can also benefit from simulation by practicing rare/complex cases, to maintain and improve their skills or even to "warm up" before performing real surgery [14]. VR simulators can be used to explore new ways of performing a procedure or to become familiar with new surgical techniques or new surgical devices [15].

Some VR simulators can assist during preoperative planning or intraoperative navigation

[16]. By reading patient-specific data obtained from medical imaging (CT or MRI), VR simulators can help to plan a surgery in order to avoid potential complications and to assure a safe outcome.

High development costs and corresponding final high price are usually mentioned as key disadvantages of VR simulators. However, when considering the wider economic benefits of better-trained surgeons, error reduction, faster completion times and savings on instructor time, VR simulators can, in fact, be cost-effective [10, 17, 18].

Lastly, there is an increasing body of evidence, which supports the transferability of surgical skills acquired through the virtual training [19]. The novel technologies have been utilized to address all aspects of modern surgical training – from learning anatomy, through development of clinical judgement and surgical planning, to acquisition of operative skills.

Anatomy

Meticulous knowledge of anatomy underpins any successful surgical training. Traditionally, anatomy has been taught through a combination of prosection, didactic lectures and self-directed textbook study. The role of cadavers has significantly decreased over the last decade, partly due to their reduced availability and the ethical issues surrounding their use [20, 21].

Various anatomical models have always been used to depict the complexities of human anatomy. The introduction of different adjuncts facilitates the creation of a mental image of a complex structure; such adjuncts also improve the efficiency of the process of memorizing and the reliability of recall. The development and advances in 3D modeling and printing, as well as simulation, have allowed for creation of new generation of high-fidelity models, which can be based on patient-specific anatomy, allowing for rehearsal of patient-tailored surgery. They can be freely moved, rotated and dissected and allow for assessment of the organ from different points of view.

Virtual models can be accessed remotely on PCs or mobile phones. Complete Anatomy by 3D4Medical and 3D Atlas by Anatomy Learning are examples of free smartphone apps that present virtual three-dimensional models. Visual Human Projects by National Library of Medicine, a free database of 3D anatomy, provides virtual models based on volumetric reconstruction of transverse CT, MRI and cryosectional photographs of the entire male and female body [22, 23].

Virtual reality platforms like Anatomage, Biodigital, Netter3DAnatomy, Visible Body, Primal Pictures and Electronic Anatomy Atlas are other examples of modern anatomy resources. 3D models can be dissected, and students can easily transfer between the microscopic and macroscopic views. This technology is also multi-user-friendly, thus facilitating a group study approach [20].

The 3D models are especially useful for complex anatomy, such as the liver, brain, vascular, pelvic or craniofacial anatomy. Organ-specific resources, such as VIRTUAL LIVER, often depict the 3D virtual models along the relevant 2D radiological studies (CT, MRI, cholangiogram) and textual information [24].

Pelvic colorectal anatomy with its complex intricacies presents significant challenges to both students and colorectal trainees. The virtual display of a 3D pelvis and its compartments [25], as well as depiction of a rectal tumour [26], or benign pathologies, such as fistula-in-ano [27], allows the learner to manipulate the image, to inspect it in detail from different perspectives and, with different transparencies of each layer, to form a comprehensive mental image of this complex anatomical region (Fig. 29.1).

Anatomical concepts can be equally difficult to comprehend, yet their full appreciation and recognition is crucial for the safety of surgical procedures. An inguinal hernia, and the distinction between the direct and indirect sacs, is one such example, where students and junior trainees commonly struggle to form the mental image. The use of 3D virtual reconstruction appears to significantly improve the understanding and is highly valued as an addition to traditional

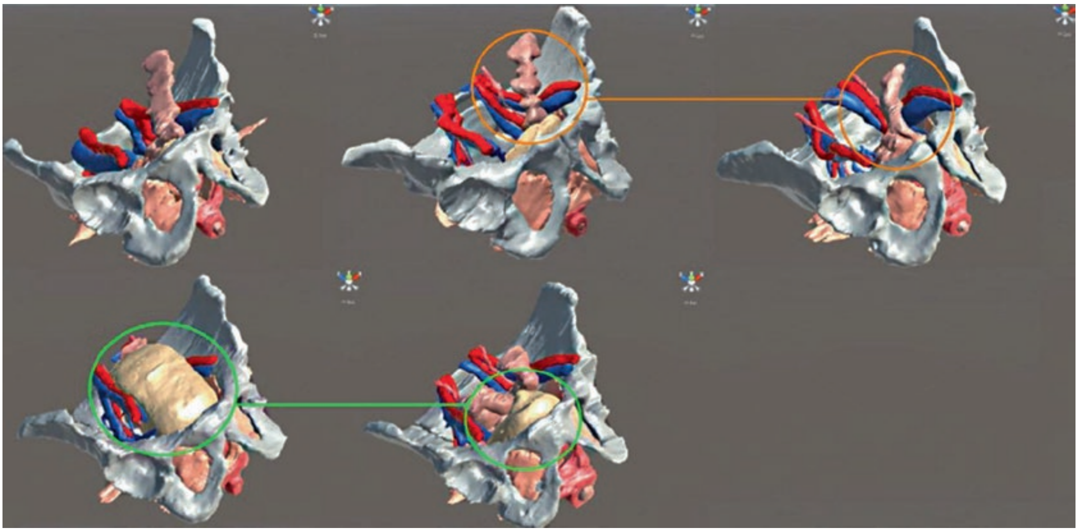

Fig. 29.1 3D models of five healthy male volunteers illustrating anatomical variation (orange) and organ distension (green)

methods. Students find preoperative review of 3D anatomy very useful for comprehension of complex intraoperative anatomy such as encountered during laparoscopic transabdominal preperitoneal repair (TAPP) [28]. Along with the virtual models, 3D printed physical models are used. These add a benefit of haptic feedback which further enhances recognition and learning [29].

Surgical Planning

Accurate operative planning is integral to the process of becoming an independent, mature surgeon. This often relies on the ability to mentally reconstruct complex two-dimensional radiological scans into three-dimensional images and then being able to interpret such reconstructions during live surgery. While there is broad evidence that 3D technology aids in surgical planning in general, it is still not widely included in surgical curricula; students report that they are not taught surgical planning enough in their training [30].

Trainees value 3D visualization highly as a useful adjunct for surgical planning. Lyn et al. found that surgical trainees assess the resectability and staging of pancreatic tumours more accurately using 3D visualization when compared with 2D staging images. It appears that 3D modeling facilitates the anatomy-image-surgery translation [31].

The same improvement in the accuracy of surgical planning and decrease in time required for that was found when virtual 3D models were used in liver surgery. Trainees saw a difference between using the 2D radiological images and 3D virtual models and reported increased confidence when forming surgical strategy with the use of 3D technology [32].

A question exists as to whether 3D *virtual* or 3D *physical* models are more efficacious. For some purposes, virtual 3D models displayed on screens offer enough information to enhance learning. However, in more complex cases, 3D printed models might be superior since they can provide the benefit of haptic feedback.

No conclusive answer exists at present; however, Zheng et al. compared the accuracy of surgical operative planning amongst students using either 3D computer or 3D printed models of patient-specific pancreatic anatomy in patients with three different types of pancreatic cancer which would require different surgical approaches. Students using the 3D printed models were able to formulate a higher-quality and more accurate operative plans [33]. This might be due to the incorporation of haptic feedback to the assessment. The authors believe that a physical model also has a more significant impact on the development of hand-eye coordination skill.

3D printed models can significantly improve inaccuracies in surgical operative planning and reduce time required for decision-making. Craniofacial surgery involves complex decision-making based on difficult anatomy that trainees are not closely familiar with. 3D printed models of craniofacial anatomy have been validated to improve these skills based on four anomalies included in the curriculum [34].

Surgical Operative Skills

One of the first medical VR simulators was developed in 1987 at Stanford University to practice Achilles tendon repair [35]. The simulator could also be used for preoperative planning. It allowed students and trainees to "walk the leg" and visualize the effect of the procedure on gait. A few years later, Lanier and Satava [8] developed a first simulator for simplified intra-abdominal surgery.

The first commercially successful VR surgical simulator was the Minimally Invasive Surgery Trainer-VR or MIST-VR [36], by Mentice AB, Sweden (www.mentice.com). It was based on abstract graphics and consisted of fundamental laparoscopic tasks emphasizing motor skills acquisition. Seymour et al. [10] demonstrated its validity and estimated a 29% reduction in operating time and an 85% decrease in number of errors during gallbladder dissection in a laparoscopic cholecystectomy procedure.

Currently, there are simulators for many subspecialties, such as laparoscopic surgery (e.g., LAP Mentor, Fig. 29.2, www.simbionix.com), endovascular surgery (e.g., Vist-Lab, www.mentice.com), endoscopy (e.g., EndoSim), etc. [37].

Patient safety is one of the main concerns in surgical training. It is especially important in the field of neurosurgery. The Immersive Touch technology has been used to develop a realistic VR platform which allows surgical trainees to perform placement of a ventriculostomy catheter. It employs 3D modeling based on a patient's CT

Fig. 29.2 Simbionix LAP Mentor laparoscopic training simulator from 3D Systems. (Courtesy of Healthcare 3D Systems, Israel)

images, combined with VR, dynamic 3D stereoscopic vision and haptic feedback. It realistically simulates the changing resistance during the passage through the brain parenchyma while the 3D visual perspective changes with the user's head movement [38].

Mental preparation is an important step in improving practice in high-performance disciplines such as extreme sports or combat aviation. Its role is being also explored in surgical education; however, unequivocal conclusions have yet to be drawn. Yiasemidou et al. argue that mental preparation in surgical trainees can be enhanced by the use of interactive models of task-relevant anatomy. This study showed that students who used interactive 3D visual models while preparing for laparoscopic cholecystectomy completed the procedure in shorter time with a smaller number of movements. It showed a promising role of 3D visualization during mental preparation for minimally invasive surgery [39].

This novel technology can be utilized to increase the objectivity of assessment of surgical skill. When the assessment is conducted on a patient, frequently, trainees are not able to perform the entire procedure and therefore only parts of it are assessed. Often, it is delivered in a descriptive way, assigning levels of competency according to a predetermined scale. Simulation, however, allows for an assessment, where the outcomes can be measured objectively. The 3D model can be easily scrutinized following the completion of the procedure which enhances the delivery of feedback as well.

Choi et al. introduced a 3D printed model of prostate, which serves both as a training and an assessment tool for surgeons. A 3D physical model has been moulded to depict with high-fidelity two distinctive zones of the prostate – it is crucial to distinguish reliably between these to perform safe transurethral resection of the prostate gland. Through applying different materials to construct these, a real-life scenario is created where a surgeon relies on haptic feedback during this minimally invasive procedure. Different sonographic contrast is applied to each zone which then allows for an objective assessment of the safety and completion of the resection [40].

Transfer of skills remains an important area specific to the development of surgeons in residency and fellowship training, which justifies the funding applied towards the use of the new technologies in surgical and medical education. It is not fully understood whether the transfer of skills is more efficient based on the similarity of the learning context [41] or the similarity of the learning process required for completion of the task [42]. Both components should be addressed in the design of simulation technologies.

VR has been employed by some groups to test educational theories. Yang et al. assessed the skill and knowledge transfer between two common types of general laparoscopic operations in surgical novices – appendectomy and cholecystectomy. It showed that previous exposure to laparoscopic appendectomy does not necessarily translate into reduction of operative time or overall safety of the procedure in laparoscopic cholecystectomy. However, it positively affected the ergonomy of surgeon movements. This study leads to the conclusion that procedure-specific learning curricula are necessary to develop skills relevant to each procedure [43]. More research in this area is required.

Adjunctively, video games – which are keenly dependent on the honing of hand-eye coordination – are being explored as tools for surgical training as well. There is some evidence that that the acquisition and practice of video gaming skills translate into surgical skills. In fact, laparoscopic surgeons who played video games regularly made fewer surgical errors [44] and were observed to be faster [45, 46] than those who did not play, suggesting a correlation with achieving adeptness at the technical aspects of operating. Similar correlations were found for endoscopic or gastroscopic skills [47, 48]. Perhaps not surprisingly, students, including those who do not play video games, support their application of video gaming as an adjunct to surgical training and, specifically, towards the acquisition of technique-based advanced surgical skill pertaining to minimally invasive surgery.

Patient Engagement

The patient's role, both in individual care and in shaping healthcare systems in general, has evolved enormously in recent years. Increasingly more focus is being placed on patient safety, measurable outcomes and overall satisfaction. Simultaneously, patients have gained an important voice in shaping clinical research and healthcare systems. A fruitful communication is paramount in achieving these goals. It leads to better adherence to treatment plans and reduced anxiety, and it achieves greater satisfaction with an overall improved patient experience.

3D modeling, simulation and VR have all been explored and show promising potential for patient engagement. The novel technologies have been explored to achieve various aims – to improve healthcare literacy, to engage the public and promote healthy habits and to design healthcare systems and research programs, further supporting the implementation of evidence-based medicine.

Improving Patient Knowledge and Health Literacy

Virtual or physical three-dimensional models of organs affected by the disease can improve patient's understanding of pathology and facilitate a more informed consent process and a more satisfactory formation of treatment plans. These models can depict generic anatomy or patient-specific pathology in a manner that laypersons, including patients, can more easily comprehend. Increasingly, more reports and clinical examples are emerging for the modeling of common pathologies, as well as complex and rare conditions [49].

Bernhard et al. assessed the impact on a patient's understanding of pathology and treatment using a 3D printed life-size, patient-specific model of renal tumours during the consent process for partial nephrectomy. They found an improved knowledge of basic kidney anatomy and physiology, as well as tumour characteristics and proposed surgical procedure, when the 3D printed models (based on patient-specific CT scans) were used [50].

Zhuang et al. explored the effectiveness of 3D virtual reconstructions and printed models of individualized patient anatomy (specifically, lumbar pathology) in increasing patient understanding of their condition and surgical plan. The group found that patients' knowledge and satisfaction were significantly improved when 3D *printed* models were used, compared to 3D *virtual* reconstructions or traditional approach using the CT and MRI images only [51].

Similarly, Kim et al. assessed the usefulness of 3D printed patient-specific models of cerebral aneurysms as an educational tool for those undergoing surgery for cerebral artery aneurysm clipping. Again, they observed an improved understanding and satisfaction of the explanation compared to the use of traditional two-dimensional CTA images [52].

Mobile applications can be used to facilitate 3D visualization of surgery leading to better patient understanding. Pulijala et al. showed that patients who used a mobile application with 3D animations (related to orthognathic surgery) retain more knowledge of the proposed procedures and their complications than a cohort of patients who receive verbal explanation only [53].

Virtual reality platforms and immersive image viewing experience have also been successfully applied to improve patient education related to specific medical conditions. Pandrangi et al. introduced standardized 3D models of abdominal aortic aneurysm (AAA) viewed in VR through Google Cardboard VR headset in patients with this condition. Despite mostly having no previous experience with use of VR, this technology was positively received by the majority of patients who felt that it significantly improved their understanding of the condition and overall engagement in their care. The overwhelming majority of patients felt comfortable using this technology and would like to see it used more frequently in their care [54].

The application of VR technology can reduce anxiety related to surgical procedures as well. Yang et al. found that patients who were familiarized with a 3D model of their own knee anatomy watched through a VR headset experienced a reduced level of anxiety prior to knee arthroscopy, when compared to the patients who received standard information regarding their preoperative MRI [55].

3D models and 3D simulation play a significant role in aesthetic surgery, where addressing and managing patient expectations might be especially paramount. The novel technology has been used as a tool for visualization of desired outcomes in breast augmentation surgery or rhinoplasty. Interestingly, despite the lack of concrete evidence that this technology improves measurable outcomes, patients had a favourable view for application of VR for select types of cosmetic surgery, such as breast augmentation [56].

The transfer of knowledge between the doctor and the patient is equally important following the surgical procedure, as it is during the planning phase. It is estimated that patients recall as little as 50% of information provided by the healthcare providers. Equally importantly, research has demonstrated that in 66% of consultations, doctors can unwillingly omit at least some of the crucial information related to patient surgical care delivery [57]. VR has been successfully tested in overcoming these barriers by constructing virtual environments, where patient-doctor interactions take place. HealthVoyager is a platform designed for children with gastrointestinal pathologies, which utilizes customizable VR software compatible with smartphones or tablets (Fig. 29.3). Through creation of an avatar, it allows a patient and their parents to familiarize themselves with the child's individual anatomy, as well as relevant clinical and procedural data. The personalized information is presented in a visual, rather than text-based way and applies an active (rather than passive) learning method. Patients can also return to and review the discussions at later time to be able to apply the clinical instructions more accurately [58]. This is important as at the time of physician-patient encounter, a high level of stress can prevent the patient and their family from absorbing details of relevance.

Novel Technologies to Treat Pain

Pain is a leading complaint in majority of surgical presentations, and most patients experience acute or chronic pain during the course of their illness. Management of pain is therefore a crucial part of surgical care. VR and video gaming have proven to be successful in management of both acute and chronic pain. Their mechanism of action is based on providing distraction during the occurrence of an unpleasant stimulus and has been validated with the use of functional MRI. Immersive VR technologies have a better analgesic effect than non-immersive technology [59].

Virtual reality distraction (VRD) has been shown to be effective in management of experimentally induced thermal pain. Patterson et al. tested the virtual reality hypnosis (VRH) by creating virtual environment where patients experienced gliding through frozen landscapes and throwing snowballs. While there might be a synergistic effect when combined with post-hypnotic suggestion, VRD has been shown to be effective, and this is independent of "hypnotizability" of the subject [60].

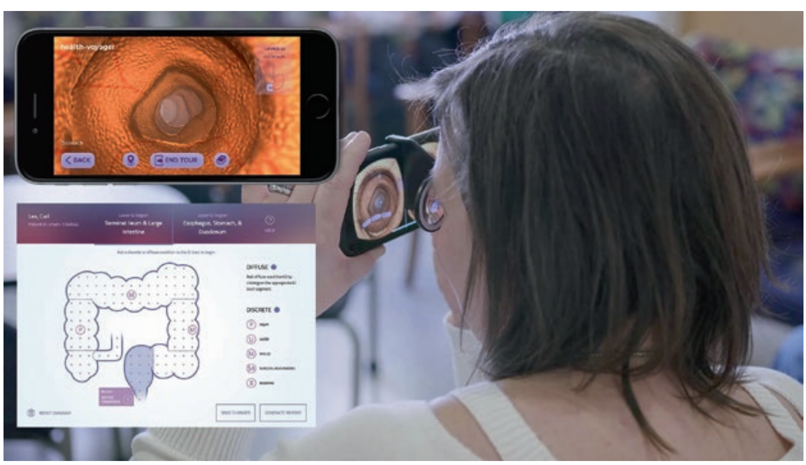

Fig. 29.3 HealthVoyager software application, with an inlay of the patient VR experience (top left) and a sample report from the physician's notes (bottom left). (From Palanica et al. [58]. Copyright © 2019, Springer Nature, Creative Commons CC BY license)

Hoffman et al. explored the use of VR in pain management in children with severe burns >10% of body surface cared for in the intensive care unit. A significant reduction in the level of most severe pain was observed when VR immersive reality (involving playing the SnowWorld, a 3D snowy canyon) was used during the wound care, when compared to patients who did not utilize VR [61].

VR technology shows promising potential as an alternative or additional treatment of chronic pain as well. Sato et al. applied virtual reality mirror visual feedback in patients with complex regional pain syndrome. A virtual environment was developed using Autodesk 3DS Max (San Rafael, USA), where the exercises are target-oriented motor-controlled tasks via various movements like reaching out, grasping, transferring and placing. In this study, 50% reduction in pain was observed in 4 out of 5 patients; furthermore, 2 out of 5 patients were able to discontinue pain clinic visits altogether [62].

Enhancing Patients' Attitudes and Promoting Healthy Lifestyle

Engaging the general public, as well as specific subgroups of patients, is important in promoting lifestyle changes. Serious video gaming has been proven to be successful in management of weight in young adults and in rehabilitation in patients with stroke or following traumatic brain injury [63–65]. It has also been used for mood management in patients with metastatic cancer.

Shaping the Future of the Healthcare Systems

There has been an important shift in the recent years from a "paternalistic" approach to healthcare, where the healthcare providers are the main decision-makers, to a model of partnership – where both patient and the care provider meet as equals with different levels of expertise. Patient and public involvement is paramount for shaping the healthcare systems and for designing clinical research.

Novel 3D technologies have been explored as a potential means to facilitate this engagement. One of the forms of obtaining patient views and arriving at solutions is a focused group discussion. Virtual worlds such as Second Life can facilitate this process through creating virtual 3D environments where meetings between patients, care providers and researchers (represented by their avatars) can take place. It can be especially attractive for patients with mobility or other restrictions, which often pose significant impedance to partaking in face-to-face interactions and dialogue. In essence, novel 3D technologies are opening new avenues for peer-led support and engagement [66].

References

1. Halsted W. The training of the surgeon. 1904.
2. Kneebone RL. Simulation reframed. Adv Simul (Lond). 2016;1:27.
3. Rosen KR. The history of medical simulation. J Crit Care. 2008;23(2):157–66.
4. Salisbury K, Conti F, Barbagli F. Haptic rendering: introductory concepts. IEEE Comput Graph. 2004;24(2):24–32.
5. Gallagher AG, Ritter EM, Champion H, Higgins G, Fried MP, Moses G, et al. Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training. Ann Surg. 2005;241(2):364–72.
6. Condino S, Carbone M, Ferrari V, Faggioni L, Peri A, Ferrari M, et al. How to build patient-specific synthetic abdominal anatomies. An innovative approach from physical toward hybrid surgical simulators. Int J Med Robot. 2011;7(2):202–13.
7. Jensen K, Ringsted C, Hansen HJ, Petersen RH, Konge L. Simulation-based training for thoracoscopic lobectomy: a randomized controlled trial: virtual-reality versus black-box simulation. Surg Endosc. 2014;28(6):1821–9.
8. Satava RM. Virtual reality surgical simulator. The first steps. Surg Endosc. 1993;7(3):203–5.
9. Satava RM. Accomplishments and challenges of surgical simulation. Surg Endosc. 2001;15(3):232–41.
10. Seymour NE, Gallagher AG, Roman SA, O'Brien MK, Bansal VK, Andersen DK, et al. Virtual reality training improves operating room performance: results of a randomized, double-blinded study. Ann Surg. 2002;236(4):458–63; discussion 63–4.
11. Youngblood PL, Srivastava S, Curet M, Heinrichs WL, Dev P, Wren SM. Comparison of training on

two laparoscopic simulators and assessment of skills transfer to surgical performance. J Am Coll Surg. 2005;200(4):546–51.
12. Zendejas B, Brydges R, Hamstra SJ, Cook DA. State of the evidence on simulation-based training for laparoscopic surgery: a systematic review. Ann Surg. 2013;257(4):586–93.
13. de Visser H, Watson MO, Salvado O, Passenger JD. Progress in virtual reality simulators for surgical training and certification. Med J Aust. 2011;194(4):S38–40.
14. Kahol K, Satava RM, Ferrara J, Smith ML. Effect of short-term pretrial practice on surgical proficiency in simulated environments: a randomized trial of the "preoperative warm-up" effect. J Am Coll Surg. 2009;208(2):255–68.
15. Punak S, Kurenov S. A simulation framework for wound closure by suture for the endo stitch suturing instrument. Stud Health Technol Inform. 2011;163:461–5.
16. Kockro RA, Serra L, Tseng-Tsai Y, Chan C, Yih-Yian S, Gim-Guan C, et al. Planning and simulation of neurosurgery in a virtual reality environment. Neurosurgery. 2000;46(1):118–35; discussion 35–7.
17. Bridges M, Diamond DL. The financial impact of teaching surgical residents in the operating room. Am J Surg. 1999;177(1):28–32.
18. Aggarwal R, Ward J, Balasundaram I, Sains P, Athanasiou T, Darzi A. Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. Ann Surg. 2007;246(5):771–9.
19. Gallagher AG, Seymour NE, Jordan-Black JA, Bunting BP, McGlade K, Satava RM. Prospective, randomized assessment of transfer of training (ToT) and transfer effectiveness ratio (TER) of virtual reality simulation training for laparoscopic skill acquisition. Ann Surg. 2013;257(6):1025–31.
20. Bisht B, Hope A, Paul MK. From papyrus leaves to bioprinting and virtual reality: history and innovation in anatomy. Anat Cell Biol. 2019;52(3):226–35.
21. Davis CR, Bates AS, Ellis H, Roberts AM. Human anatomy: let the students tell us how to teach. Anat Sci Educ. 2014;7(4):262–72.
22. Spitzer VM, Whitlock DG. The Visible Human Dataset: the anatomical platform for human simulation. Anat Rec. 1998;253(2):49–57.
23. Dai JX, Chung MS, Qu RM, Yuan L, Liu SW, Shin DS. The Visible Human Projects in Korea and China with improved images and diverse applications. Surg Radiol Anat. 2012;34(6):527–34.
24. Crossingham JL, Jenkinson J, Woolridge N, Gallinger S, Tait GA, Moulton CA. Interpreting three-dimensional structures from two-dimensional images: a web-based interactive 3D teaching model of surgical liver anatomy. HPB (Oxford). 2009;11(6):523–8.
25. Kontovounisios C, Tekkis P, Bello F. 3D imaging and printing in pelvic colorectal cancer: 'The New Kid on the Block'. Tech Coloproctol. 2019;23(2):171–3.
26. Sahnan K, Pellino G, Adegbola SO, Tozer PJ, Chandrasinghe P, Miskovic D, et al. Development of a model of three-dimensional imaging for the preoperative planning of TaTME. Tech Coloproctol. 2018;22(1):59–63.
27. Sahnan K, Adegbola SO, Tozer PJ, Gupta A, Baldwin-Cleland R, Yassin N, et al. Improving the understanding of perianal Crohn fistula through 3D modeling. Ann Surg. 2018;267(6):e105–e7.
28. Wada Y, Nishi M, Yoshikawa K, Higashijima J, Miyatani T, Tokunaga T, et al. Usefulness of virtual three-dimensional image analysis in inguinal hernia as an educational tool. Surg Endosc. 2019;34(5):1923–8.
29. Marconi S, Pugliese L, Botti M, Peri A, Cavazzi E, Latteri S, et al. Value of 3D printing for the comprehension of surgical anatomy. Surg Endosc. 2017;31(10):4102–10.
30. Snyder RA, Tarpley MJ, Tarpley JL, Davidson M, Brophy C, Dattilo JB. Teaching in the operating room: results of a national survey. J Surg Educ. 2012;69(5):643–9.
31. Lin C, Gao J, Zheng H, Zhao J, Yang H, Lin G, et al. Three-dimensional visualization technology used in pancreatic surgery: a valuable tool for surgical trainees. J Gastrointest Surg. 2019;24(4):866–73.
32. Yeo CT, MacDonald A, Ungi T, Lasso A, Jalink D, Zevin B, et al. Utility of 3D reconstruction of 2D liver computed tomography/magnetic resonance images as a surgical planning tool for residents in liver resection surgery. J Surg Educ. 2018;75(3):792–7.
33. Zheng YX, Yu DF, Zhao JG, Wu YL, Zheng B. 3D Printout models vs. 3D-rendered images: which is better for preoperative planning? J Surg Educ. 2016;73(3):518–23.
34. Lobb DC, Cottler P, Dart D, Black JS. The use of patient-specific three-dimensional printed surgical models enhances plastic surgery resident education in craniofacial surgery. J Craniofac Surg. 2019;30(2):339–41.
35. Delp SL, Loan JP, Hoy MG, Zajac FE, Topp EL, Rosen JM. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. IEEE Trans Biomed Eng. 1990;37(8):757–67.
36. Wilson MS, Middlebrook A, Sutton C, Stone R, McCloy RF. MIST VR: a virtual reality trainer for laparoscopic surgery assesses performance. Ann R Coll Surg Engl. 1997;79(6):403–4.
37. Dunkin B, Adrales GL, Apelgren K, Mellinger JD. Surgical simulation: a current review. Surg Endosc Other Interv Tech. 2007;21(3):357–66.
38. Lemole GM Jr, Banerjee PP, Luciano C, Neckrysh S, Charbel FT. Virtual reality in neurosurgical education: part-task ventriculostomy simulation with dynamic visual and haptic feedback. Neurosurgery. 2007;61(1):142–8; discussion 8–9.
39. Yiasemidou M, Glassman D, Mushtaq F, Athanasiou C, Williams MM, Jayne D, et al. Mental practice with interactive 3D visual aids enhances surgical performance. Surg Endosc. 2017;31(10):4111–7.
40. Choi E, Adams F, Palagi S, Gengenbacher A, Schlager D, Muller PF, et al. A high-fidelity phantom for the simulation and quantitative evaluation of transure-

thral resection of the prostate. Ann Biomed Eng. 2019;48(1):437–46.
41. Thorndike EL. Educational Psychology. Science. 1923;57(1476):430.
42. Lee T. Transfer-appropriate processing: a framework for conceptualizing practice effects in motor learning. Adv Psychol. 1988;50:201–15.
43. Yang C, Kalinitschenko U, Helmert JR, Weitz J, Reissfelder C, Mees ST. Transferability of laparoscopic skills using the virtual reality simulator. Surg Endosc. 2018;32(10):4132–7.
44. Grantcharov TP, Bardram L, Funch-Jensen P, Rosenberg J. Impact of hand dominance, gender, and experience with computer games on performance in virtual reality laparoscopy. Surg Endosc. 2003;17(7):1082–5.
45. Rosser JC Jr, Lynch PJ, Cuddihy L, Gentile DA, Klonsky J, Merrell R. The impact of video games on training surgeons in the 21st century. Arch Surg. 2007;142(2):181–6; discussion 6.
46. Schlickum MK, Hedman L, Enochsson L, Kjellin A, Fellander-Tsai L. Systematic video game training in surgical novices improves performance in virtual reality endoscopic surgical simulators: a prospective randomized study. World J Surg. 2009;33(11):2360–7.
47. Stefanidis D, Acker C, Heniford BT. Proficiency-based laparoscopic simulator training leads to improved operating room skill that is resistant to decay. Surg Innov. 2008;15(1):69–73.
48. Westman B, Ritter EM, Kjellin A, Torkvist L, Wredmark T, Fellander-Tsai L, et al. Visuospatial abilities correlate with performance of senior endoscopy specialist in simulated colonoscopy. J Gastrointest Surg. 2006;10(4):593–9.
49. Aroney N, Markham R, Putrino A, Crowhurst J, Wall D, Scalia G, et al. Three-dimensional printed cardiac fistulae: a case series. Eur Heart J Case Rep. 2019;3(2)
50. Bernhard JC, Isotani S, Matsugasumi T, Duddalwar V, Hung AJ, Suer E, et al. Personalized 3D printed model of kidney and tumor anatomy: a useful tool for patient education. World J Urol. 2016;34(3):337–45.
51. Zhuang YD, Zhou MC, Liu SC, Wu JF, Wang R, Chen CM. Effectiveness of personalized 3D printed models for patient education in degenerative lumbar disease. Patient Educ Couns. 2019;102(10):1875–81.
52. Kim PS, Choi CH, Han IH, Lee JH, Choi HJ, Lee JI. Obtaining informed consent using patient specific 3D printing cerebral aneurysm model. J Korean Neurosurg Soc. 2019;62(4):398–404.
53. Pulijala Y, Ma M, Ju X, Benington P, Ayoub A. Efficacy of three-dimensional visualization in mobile apps for patient education regarding orthognathic surgery. Int J Oral Maxillofac Surg. 2016;45(9):1081–5.
54. Pandrangi VC, Gaston B, Appelbaum NP, Albuquerque FC Jr, Levy MM, Larson RA. The application of virtual reality in patient education. Ann Vasc Surg. 2019;59:184–9.
55. Yang JH, Ryu JJ, Nam E, Lee HS, Lee JK. Effects of preoperative virtual reality magnetic resonance imaging on preoperative anxiety in patients undergoing arthroscopic knee surgery: a randomized controlled study. Arthroscopy. 2019;35(8):2394–9.
56. Overschmidt B, Qureshi AA, Parikh RP, Yan Y, Tenenbaum MM, Myckatyn TM. A prospective evaluation of three-dimensional image simulation: patient-reported outcomes and mammometrics in primary breast augmentation. Plast Reconstr Surg. 2018;142(2):133e–44e.
57. Tarn DM, Heritage J, Paterniti DA, Hays RD, Kravitz RL, Wenger NS. Physician communication when prescribing new medications. Arch Intern Med. 2006;166(17):1855–62.
58. Palanica A, Docktor MJ, Lee A, Fossat Y. Using mobile virtual reality to enhance medical comprehension and satisfaction in patients and their families. Perspect Med Educ. 2019;8(2):123–7. https://doi.org/10.1007/s40037-019-0504-7.
59. Gold JI, Kim SH, Kant AJ, Joseph MH, Rizzo AS. Effectiveness of virtual reality for pediatric pain distraction during i.v. placement. Cyberpsychol Behav. 2006;9(2):207–12.
60. Patterson DR, Hoffman HG, Palacios AG, Jensen MJ. Analgesic effects of posthypnotic suggestions and virtual reality distraction on thermal pain. J Abnorm Psychol. 2006;115(4):834–41.
61. Hoffman HG, Rodriguez RA, Gonzalez M, Bernardy M, Pena R, Beck W, et al. Immersive virtual reality as an adjunctive non-opioid analgesic for predominantly Latin American children with large severe burn wounds during burn wound cleaning in the intensive care unit: a pilot study. Front Hum Neurosci. 2019;13:262.
62. Sato K, Fukumori S, Matsusaki T, Maruo T, Ishikawa S, Nishie H, et al. Nonimmersive virtual reality mirror visual feedback therapy and its application for the treatment of complex regional pain syndrome: an open-label pilot study. Pain Med. 2010;11(4):622–9.
63. Sietsema JM, Nelson DL, Mulder RM, Mervau-Scheidel D, White BE. The use of a game to promote arm reach in persons with traumatic brain injury. Am J Occup Ther. 1993;47(1):19–24.
64. Caglio M, Latini-Corazzini L, D'Agata F, Cauda F, Sacco K, Monteverdi S, et al. Video game play changes spatial and verbal memory: rehabilitation of a single case with traumatic brain injury. Cogn Process. 2009;10(Suppl 2):S195–7.
65. Caglio M, Latini-Corazzini L, D'Agata F, Cauda F, Sacco K, Monteverdi S, et al. Virtual navigation for memory rehabilitation in a traumatic brain injured patient. Neurocase. 2012;18(2):123–31.
66. Taylor MJ, Kaur M, Sharma U, Taylor D, Reed JE, Darzi A. Using virtual worlds for patient and public engagement. Int J Technol Knowl Soc. 2013;9(2):31–48.