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REVIEW PAPER

The role of simulation in neurosurgery

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Abstract
Purpose In an era of residency duty-hour restrictions, there has been a recent effort to implement simulation-based training methods in neurosurgery teaching institutions. Several surgical simulators have been developed, ranging from physical models to sophisticated virtual reality systems. To date, there is a paucity of information describing the clinical benefits of existing simulators and the assessment strategies to help implement them into neurosurgical curricula. Here, we present a systematic review of the current models of simulation and discuss the state-of-the-art and future directions for simulation in neurosurgery.
Methods Retrospective literature review.
Results Multiple simulators have been developed for neurosurgical training, including those for minimally invasive procedures, vascular, skull base, pediatric, tumor resection, functional neurosurgery, and spine surgery. The pros and cons of existing systems are reviewed.
Conclusion Advances in imaging and computer technology have led to the development of different simulation models to complement traditional surgical training. Sophisticated virtual reality (VR) simulators with haptic feedback and impressive imaging technology have provided novel options for training in neurosurgery. Breakthrough training simulation using 3D printing technology holds promise for future simulation practice, proving high-fidelity patient-specific models to complement residency surgical learning.

Keywords Simulation · Virtual reality · 3D printing · Residency · Duty hours · Neurosurgery

Introduction

Simulation involves the use of models to imitate real-life experience. It has gained widespread acceptance in many fields, including for aviation safety, war strategies, and in the medicine. Many of these areas involve high-stake scenarios where mistakes or failures can have disastrous consequences. As such, much value has been placed in allowing practitioners and trainees to perfect their skills, refine techniques, and avert costly mistakes before working in the actual clinical arena.

Neurosurgery is a complex field requiring thoughtful judgment, technical expertise, and meticulous focus. Given these factors, there has been a recent surge of interest in neurosurgical simulation. This is largely due to the confluence of two synchronous factors: reduced exposure of trainees to surgical cases based on residency duty-hour restrictions and technological advances in imaging, computation, virtual reality (VR), and 3D printing in the field of simulation.

As the field of neurosurgery continues to advance, it has become clear that the operating room is not the ideal place for the initial acquisition and refinement of surgical skills. The sequence of maneuvers in clinical practice can rarely be repeated if failure occurs. Simulation affords surgeon and trainee the opportunity to rehearse the procedure beforehand and take a “practice swing” before actually hitting the ball. Neurosurgical simulation offers realistic opportunities to

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enhance the safety and efficacy of both straightforward and complex operative procedures.

Here, we review the evolution of neurosurgical simulation and discuss the current state-of-the-art and future directions for the field.

Simulation background

History of simulation and medical simulation

Throughout history, simulation has been used as a means to practice difficult procedures and maneuvers by novices and experts. For centuries, the military has used war games for decision-making and operational strategies. As early as 500 BC, Greeks began playing *petteia*, a board game modeled on war to plan military tactics [1] (Fig. 1). Chess, one of the earliest attempts of gaming strategy, originated from the two-player Indian military game in the sixth century [2]. In all its variations, chess has been used to illustrate war tactics and probe new strategies. During the nineteenth century, the Prussian army designed the *Kriegsspiel*, a military game and leading model for modern computerized warfare simulations developed by Georg von Rassewitz in 1812 [3] (Fig. 2). Those strategic tools enabled the military to improve thinking and training in the battlefield [4].

During the post-cold war period, the US Department of Defense was engaged in an ambitious entrepreneurial approach toward the computer industry at large. Simulator networking (SIMNET), the major simulation military training technology during the 1980s, was responsible for the unprecedented innovation leading to computer simulation in real time, both for military training and for multiuser simulation practice. Initially developed to anticipate conflict and guide military tactics, the system was used as a means to analyze the effectiveness of training through wartime simulation [5]. The unifying principle of military simulation and planning strategies is basically to write history in advance, by simulating real-life situations beforehand [6].

Fig. 1 Achilles and Ajax playing the board game *Petteia*, a board game designed for military tactics

Fig. 2 Officers playing Kriegsspiel, German word for "war game," a chess variant developed in 1812

The earliest simulation attempt in medicine was cadaveric dissection during the era of Alcmaeon of Croton, a Greek philosopher in the sixth century BC [7]. In 275 BC, Herophilus of Chalcedon (335–280 BC), founder of the first school of anatomy in Alexandria, encouraged human cadaveric studies, leading to significant advancements in the medical knowledge [8, 9] (Fig. 3). The works of Leonardo da Vinci (1452–1519) (Fig. 4), Andreas Vesalius (1514–1564) (Fig. 5), and others who followed Galen (AD 129–c.200/c.216) provided further clarification of human body [6, 10].

Limitations of cadaveric models encouraged the development of physical models to reproduce human-like responses

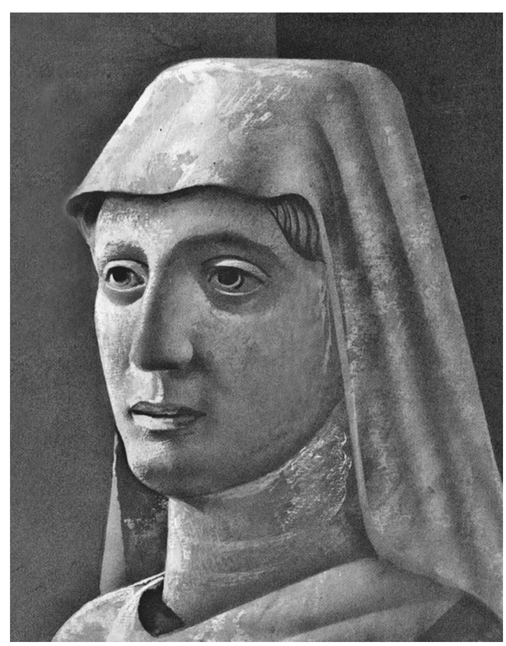

Fig. 3 Portrait of Herophilus of Chalcedon (335–280 BC). Herophilus encouraged human cadaveric studies that led to significant advancements in medicine. Collection of the Houston Academy of Medicine—Texas Medical Library

Fig. 4 Leonardo da Vinci (1452–1519), a genius of the Renaissance period, injected blood vessels and cerebral ventricles with wax for preservation and anatomical study

for medical training. The synthetic trainers initiated with the creation of "Resusci-Anne," a cardiopulmonary resuscitation manikin developed by Åsmud Lærdal, a Norwegian publisher and toy manufacturer in the 1950s [11, 12] (Fig. 6). In the late 1960s, Abrahamson and Denson at the University of Southern California created the first anesthesia simulator, SimOne (Aerojet General Co., California), a computer-controlled manikin [13]. The trainer reproduced physiologic responses such as breathing movements, synchronized arterial pulses, and blood pressure [8]. In the early 1980s, David Gaba, from the Stanford University, and Michael Good and JS Gravenstein, from the University of Florida, developed high-fidelity anesthesia simulators [6, 12]. The former group created the Comprehensive Anesthesia Simulation Environment (CASE), and the latter team developed the Gainesville Anesthesia Simulator (GAS) [8, 12].

Current concepts of simulation training are modeled primarily on methods implemented by the aviation industry in early twentieth century. Since the 1930s, flight simulation has become a training requisite for commercial and military pilots [6]. The same principle used in flight simulation has been applied to assist surgeons. In medical education, simulation training is defined as "a technique to replace or amplify real patient experiences with guided experiences, artificially contrived that evokes or replicates substantial aspects of the real world in a fully interactive manner" [14].

More recently, the American Council of Graduate Medical Education (ACGME) implemented restrictions of residency duty hours to an 80-h work week aiming to improve patient safety and residents' quality of life [15]. Since then, the ACGME has encouraged medical institutions to implement alternative methods of residency training [16]. Currently,

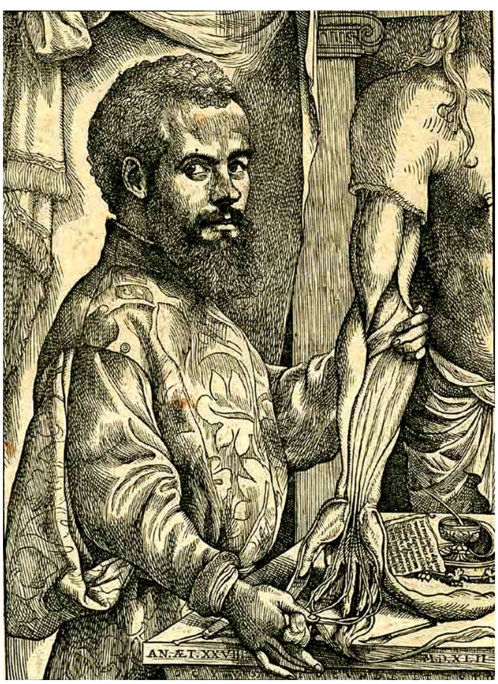

Fig. 5 Andreas Vesalius (1514–1564), the founder of modern human anatomy, provided further knowledge of anatomy-based systematic cadaveric dissection

Fig. 6 Åsmud Lærdal (1914–1981), creator of the first synthetic human trainer, the Resusci-Anne. Photo courtesy of Laerdal Medical. All rights reserved

approximately 70 % of medical schools have already incorporated some type of simulation in their curricula, especially in procedure-based specialties, such as general surgery, urology, and neurosurgery [10].

A recent survey of neurosurgery program directors across the USA concluded that simulation is considered an important tool to complement traditional operative training [17]. Therefore, there has been a burgeoning interest in newer and effective methods to expose trainees to difficult tasks during the residency years [18]. Simulation-based training offers an opportunity to meet the ACGME requirement. However, the long-term effects of such a change are not yet known.

Type of simulators

Simulation trainers are classified as *physical models*, *virtual reality*, and *mixed-reality* simulators [19, 20]. Animals and human cadavers, so-called physical models, have been considered standard methods for surgical training in the past [21, 22]. However, they have a number of limitations, which include biological and practical restrictions, such as biohazard safety, tissue rigidity, and length of preservation. Also, formalin-fixed brains fail to accurately represent surgical parameters, including vascular pulsation and dynamics [8, 23].

The second type of surgical simulator is virtual reality. With the development of computed tomography (CT) and magnetic resonance imaging (MRI) techniques, the construction of 3D interactive systems has enabled trainees to navigate in the cranial and spinal anatomy (Fig. 7) [6]. One of the greatest obstacles in developing VR models is to reproduce the elasticity of tissue deformation, especially complex layered and nonhomogeneous structure of soft tissue [10, 20, 22, 24–27].

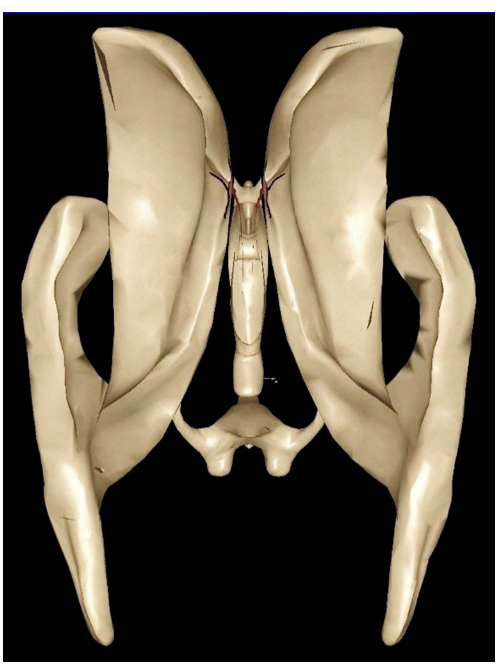

Fig. 7 VR patient-specific ventricular system rendered from MRI, view from the bottom surface

Mixed-reality simulator, known as hybrid simulator, is the third type of surgical trainer [10, 28]. The system consists of a physical and virtual component, in which the trainees perceive both the physical environment around them and the virtual elements coexisting in the same space [10, 20, 29, 30]. Thus, this simulator provides hints for real-world training, integrating patient-specific characteristics and virtual system [21, 22].

Simulation design

Simulation-based models enable trainees to reproduce techniques in a safe environment and to obtain objective performance evaluation for each task [31]. Once the model is designed, it must be evaluated according to psychometric tests to ensure that educational practices are reliable and valid [32–34]. Structured assessments of technical skills are evaluated based on two criteria: *validity* and *reliability.*

Validity describes the extent by which the model measures what it is made to measure, that is "the property of being true, correct, and in conformity with reality" [35]. Among the benchmarks to assess validity, there are the concepts of face, content, construct, and criterion [36]. *Face validity* or realism describes the extent to which the test simulates the condition in the real world. *Content validity* represents the extent to which the measurement reflects the attributes it purports to measure [36]. The minimum requirement for simulator approval is *construct validity*, which describes objectively if the test is measuring the construct it claims to be measuring. Mainly, it should be able to distinguish the performance between a junior and senior surgeon [31, 36]. *Criterion validity* corresponds to the extent to which an assessment tool correlates with different performance's measurements.

Reliability assessment measures whether the same result is obtained on repeated trials or under consistent conditions [35]. It describes the possible similar results obtained by two surgeons with the same experience or by one surgeon repeating the test without enhancement of skills [28, 37–39]. With this broad perspective of simulation models, we will highlight the use of simulators in the different subspecialties of neurosurgery.

Simulation for general neurosurgery

The mastery of fundamental technical skills to provide safe patient care is a prerequisite of all neurosurgeons. By the end of residency training, treating life-threatening neurological illnesses becomes second nature, but like any technique, these "basic skills" must be sharpened. Simulators in general neurosurgery are beneficial in training junior residents and for the continuing education of subspecialized neurosurgeons that intermittently need to provide general call services to their communities.

General skills include operative techniques, emergent procedures, as well as care for the critically ill neurointensive patient [40]. Musacchio et al. presented a critical care-training program using Human Patient Simulator ™ for neurosurgical trainees. Topics included spinal shock, closed head injury, and cerebral vasospasm. Based on their experience, the neurosurgical critical care simulator helped residents and students to enhance their critical care education and the benefit for learning in a fail-safe scenario [41].

Simulation for operative basics is also being explored with trainers to teach hemostasis techniques during cranial surgery. Gasco et al. reported a novel VR simulator for hemostasis and presented the possible benefits to improve eye-hand coordination and depth perception. However, validation for this type of simulation need to be further developed [42].

Emergency neurosurgical procedures, including ventriculostomy and decompressive craniectomy, are typically learned on patients in times of elevated stress. Burr hole and trauma craniotomy simulators have been developed by the National Capital Area Simulation Center (Uniformed Services University, Bethesda, Maryland) to teach residents as well as military surgeons who are being deployed to manage neurotrauma cases [43, 44]. Also, there have been several reports on ventriculostomy simulators that demonstrate validated learning experiences for the treatment of neurosurgical emergencies, including VR models with haptic feedback and mixed-reality simulator [45–48].

Vascular neurosurgery

The field of vascular neurosurgery has undergone remarkable transformation in the past 25 years, especially in neuroendovascular therapy [49]. Advances in this field have been induced by improving materials science technology, leading to the development of novel devices and delivery tools that are effective and safe [50]. Moreover, as the indications for endovascular therapy rise, a decrease in traditional microsurgery is observed, creating a void in trainee education for aneurysm clipping and bypass techniques.

New avenues to complement vascular neurosurgical training have been reported [23, 51–53]. In 2002, Aboud et al. introduced a cadaveric model with colored fluid under pulsating pressure for arteries simulating live surgery [54]. The use of human placenta for vascular training is another alternative that can be used to create aneurysm models for clipping and endovascular treatment [55, 56].

Bypass simulators range from physical models to VR trainers [57]. A proposed model for neurovascular simulation training starts with the novice practicing the procedure on synthetic and VR simulators, followed by a progression to animal and human tissues. Validation and reliability assessments for this process have yet to be fully tested [57, 58].

Advances in cerebrovascular imaging with 3D CT angiography and 3D digital subtraction angiography have enabled the creation of complex aneurysm simulators. From this highly developed platform, synthetic 3D elastic models can be rapidly prototyped to enhance understanding of aneurysm structure in both the OR and endovascular suite [59, 60]. Additionally VR and stereoscopic analysis can be created for educational and surgical planning [61, 62].

High-fidelity endovascular simulation offers a means for mentored instruction in a realistic scenario. Neuroangiography has offered a road map for simulated opportunities in other specialties, including vascular surgery, interventional radiology, and cardiology. A strong correlation has been demonstrated between technical simulator skills and clinical endovascular experience [63–65].

In a simulation-based practice, the interventionalist can make procedural errors and experience the consequences in a safe learning environment [66]. Several courses utilizing simulator-based angiography have been held to date and have been seen as benefiting the education of trainees [50]. As a result, endovascular simulation is likely to become fully integrated in both resident and fellowship training [67].

Minimally invasive neurosurgery

Advances in minimally invasive procedures have made the neurosurgical community rethink residency training. As new complex techniques and instruments are introduced, preoperative planning and anatomical knowledge alone are insufficient for carrying out the surgical procedure [68, 69]. Therefore, different minimally invasive simulators have been recently introduced to the field to improve preoperative planning and increase safety of neuroendoscopy surgery [22] (Fig. 8).

Several 3D visualization systems for preplanning intraventricular surgery have been developed to assist trainees in clinical decision-making prior to the actual procedure [70]. ROBO-SIM, originally for use with NEUROBOT (Fokker Control Systems, Schiphol, The Netherlands), was designed for manipulator-assisted virtual procedures in minimally invasive neurosurgery [71, 72]. The system enables neurosurgeons to simulate operative procedures directly on the patient's anatomy while looking at a virtual scenario [72].

Different virtual endoscopy systems have been developed to enable trainees to simulate operative procedures while becoming familiar with the minimally invasive instruments [24]. A team of engineers and neurosurgeons from the University of Tübingen, Germany, developed a virtual neuroendoscopy

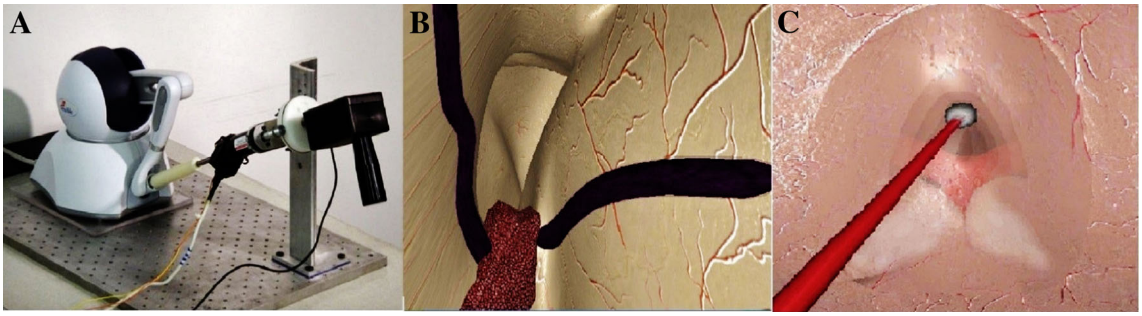

Fig. 8 VR neuroendoscopy trainer. **a** VR trainer and haptic testing. **b** VR image, right lateral ventricle, showing the anterior septal vein, foramen of Monro, choroid plexus, and thalamostriate vein. **c** VR image of the floor of the third ventricle, showing the fenestration at the tuber cinereum using a fogarty catheter

system for surgical planning known as VIVENDI [73, 74]. The developers stated that VIVENDI is a helpful tool assisting neurosurgeons in operative planning and intraoperative orientation [73, 75].

Recently, the National Research Council Canada (NRCC) and affiliated institutions developed the NeuroTouch Endo. The VR platform is a simulator for endoscopic transsphenoidal surgery that integrates haptic feedback via tactile tool manipulators [76]. The inventors state that the system enables the trainees to practice minimally invasive techniques in both anatomical and pathological scenarios [74].

Brain tumor resection

The Dextroscope (Bracco AMT, Princeton, New Jersey) is a VR system that enables surgeons to interact with and manipulate the virtual patient [77]. Currently, the use of the Dextroscope has been reported for several neurosurgical clinical scenarios, including vascular pathologies, cranial nerve decompression, tumor resection, and epilepsy procedures [78]. The developers believe that this system has assisted novice surgeons to develop basic psychomotor and visual-spatial skills [79, 80].

Kockro et al. developed a Dextroscope-based system, known as Virtual Intracranial Visualization and Navigation (VIVIAN) [77]. The navigation system provides 3D visualization of the surgical field and its surroundings. According to the authors' description, the system assists trainees in carrying out complex procedures, including preoperative planning for skull base surgery.

The NRCC and affiliated institutions developed the NeuroTouch Cranio, a VR simulator for brain tumor resection. The trainer enables the participants to manipulate surgical tools and provides haptic feedback during simulation [76]. The device computes the resident's performance at the end of the procedure by evaluating the time of task completion and the amount of virtual tissue removal [33, 81].

Pediatric neurosurgery

In 2007, Rodt et al. introduced a computer-assisted 3D visualization and simulation system for fronto-orbital advancement in children with trigonocephaly [82]. The 3D imaging simulator was used as a complementary tool in preplanning the surgical intervention. The authors believe that the system helps surgeons to optimize operative planning, especially in complex cases like metopic synostosis.

Recently, Coelho et al. developed a synthetic trainer for craniosynostosis procedures. Known as the Anatomical Simulator for Pediatric Neurosurgery (ASPEN; Pro Delphus, São Paulo, Brazil), the scaphocephaly simulator enables surgeons to practice and rehearse open craniosynostosis technique [83]. Although further validation assessments must be tested prior to its implementation in the surgical curricula, the model represents a feasible method for neurosurgical training.

A novel pediatric neurosurgery simulator has been described by Mattei et al. The authors, in a joint program with the Mechanical Engineering Department of Bradley University and the Department of Neurosurgery of the University of Illinois, developed a synthetic trainer for pediatric lumbar pathologies. The simulator reproduces different scenarios commonly encountered in pediatric neurosurgery, including myelomeningocele and tethered spinal cord [25].

Stereotactic radiosurgery

Stereotactic radiosurgery (SRS) has become an important treatment modality for brain tumors and vascular malformations [84–86]. Radiosurgery induces fibrosis or gliosis within the irradiated tissue, and excessive doses have the potential to induce necrosis or unwanted damage to the surrounding structures [87]. Simulation technology and sophisticated techniques in radiosurgery have been developed to provide accurate placement of the intended radiation [85, 88].

Monte Carlo simulations are 3D dosimetry tools suitable for adequate SRS therapy [89, 90]. They use random number generation and probability statistics to solve different physics-based mathematical problems [91, 92]. Although they are considered the most accurate and sensitive method for simulating radiation transport, the medical physics community recognizes the necessity to develop more sophisticated system [93].

Dieterich et al. introduced guidelines to robotic radiosurgery systems for preplanning intervention and verification of the radiation-target properties. According to the authors, anthropomorphic phantoms can assist in determining the target boundaries, especially when these models are a close structural match to the patient's anatomy. Also, phantoms are suitable prototypes to detect variations in accuracy when imaging system is less than optimal [88, 90].

Radiation toxicity to the optic nerves and chiasm, pituitary gland, and surrounding tissue may be deleterious, resulting in irreversible deficits [85]. To reduce radiation toxicity to the optic radiation, Hamamoto et al. introduced a tractography simulator to estimate dose tolerance of the optic radiation. The authors believe that the simulator system might be an effective device in preventing postradiation visual disturbances and headaches [94].

Virtual radiosurgery simulation provides a means to maximize target exposure and procedural safety [85]. The virtual system assists in clinical decision-making, defines surgical targets, and optimizes radiation dose planning. This can be especially helpful in complex cases in which the most adequate choices are not directly apparent [35, 85].

Skull base neurosurgery

Skull base neurosurgery remains technically challenging, as it requires comprehensive understanding of 3D anatomy and development of operative skills' competency [95]. Virtual reality platforms have the potential to assist neurosurgeons in defining the surgical landmarks and choosing the most suitable approach [96, 97]. Also, interactive virtual simulators with haptic rendering might be a promising tool for residents to practice skull base procedures in a 3D VR environment [95, 98].

Voxel-Man Group (Hamburg, Germany) developed VR temporal bone simulators based on high-resolution volumetric CT images [24, 99–101]. The developers described the benefits of the trainer, including highly detailed visual and haptic rendering of the surfaces. The simulators were felt to improve the realism of surgical procedures in the middle ear and provided automatic skills assessment for each participant by the end of the procedure [99, 102].

Spine surgery

Spine surgery has become increasingly the domain of neurosurgery, while traditionally having deep roots within the orthopedic community. Thus, the push for increased practice and simulation is not only at the training level (residency and fellowship) but also for practitioners [103]. Surgical techniques used in spinal instrumentation simulation include (1) identification of anatomical landmarks for screw entry points, (2) the use of fluoroscopy with interpretation before placement of screws, and (3) the use of intraoperative registration and navigation systems for proper screw insertion [20].

Different simulators have been created to assist surgical training in spine surgery. ImmmersiveTouch (Immersive Touch, Inc., Chicago, Illinois, USA), a VR platform combined with haptic technology called Sensimmer®, has recently developed a lumbar pedicle screw model [101]. In a randomized trial of novice participants, the authors showed a significant improvement of pedicle screw placement among those who had training using the VR model compared to those only exposed to the traditional didactic method.

Bova et al. recently described a patient-specific mixed-reality simulator for spine procedures [20]. The trainer enables the participant to choose the correct screw to be inserted and to evaluate its trajectory within the pedicle. Although it is an interesting simulation method for percutaneous screw placement, no objective test of its validity and reliability has been reported.

A percutaneous VR simulator for vertebroplasty has also been developed to assist trainees during their neurosurgical training. Chui et al. described a virtual spine trainer for simulating polymethyl methacrylate (PMMA) or cement injection [104]. The module is a variant of a percutaneous pedicle screw placement system, and it is felt to assist residents to practice the technique in a safe environment [24].

Functional neurosurgery

Stereotactic and Functional Neurosurgery, which involves a wide range of procedures including deep brain stimulation (DBS), epilepsy surgery, and microvascular decompression, has had an intimate relationship with simulation that is continuously evolving. Deep brain stimulation is highly dependent on stereotactic navigation and precise trajectory planning. Because of the similarity between this procedure and the placement of external ventricular drains (EVDs), many of the physical, VR, and mixed-reality simulation systems for EVDs may be suitable for DBS planning [46].

The most devastating complication of DBS procedures is intracranial hemorrhage, occurring in approximately 3 % of cases [105]. Nowinski et al. introduced a DBS simulator system based on a reconstruction of a 3D stereotactic atlas of

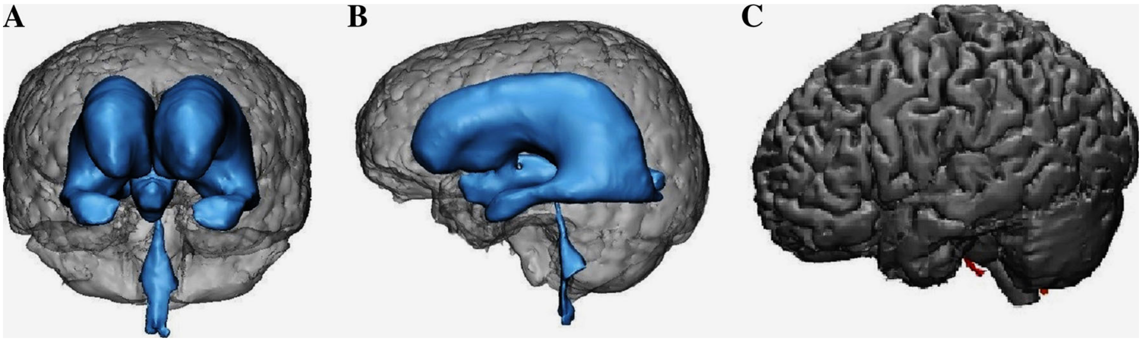

Fig. 9 Digital 3D surface of the ventricular system (**a**, **b**) and brain (**c**) generated from the preoperative rendered MRI studies of a 14-year-old patient with hydrocephalus

brain structure and vasculature using MR studies. The authors believe that the DBS simulator can assist neurosurgeons to place electrodes effectively, thus reducing postoperative complications [106].

For stereotactic electrode placement in epilepsy surgery, many of the software programs used in preplanning DBS operations can be utilized in finding ictal zones. Advances in imaging technology have led to the development of multimodality neuroimaging data in 3D virtual scenario, thus potentially increasing the accuracy of electrode placement [107, 108]. Also, novel imaging techniques can assist surgeons to determine the exact location of the electrodes in cases of postoperative parenchymal shift [109, 110].

Future directions

The ACGME has encouraged teaching institutions to incorporate simulation methods in the surgical curricula thus complementing traditional education. The implementation of these methods can help meet the six common competencies described by the ACGME: patient care, medical knowledge, practice-based learning and improvement, interpersonal and communication skills, professionalism, and system-based practice [111]. Ultimately, simulation-based training has the potential to enhance safety and predictability of operative procedures.

Currently, 3D printing has been used primarily in three major areas in medicine: (1) operative planning, teaching, and practice; (2) implantation of prosthetics; and (3) biologic tissue engineering. Advances in 3D printing have enabled scientists, engineers, and physicians to create models for surgical planning and residency training [100, 112–114] based on patient-specific imaging studies (Fig. 9). High-fidelity 3D printed models have the potential to assist clinical decision and allow surgeons to rehearse neurosurgical cases in a manner not previously possible.

Multimaterial 3D printers have the capability to create high-fidelity multitexture models for operative planning and training. The prototype provides means for the surgeon to develop a superior understanding of the operative anatomy and the technique, thus improving operative planning through the ability to interact a patient-specific model [115]. In the field of epilepsy, 3D models have the potential to improve neurosurgical planning such as implantable electrode grid placement. A physical high-fidelity 3D prototype enables surgeons to precise spatial fits and anticipate operative complications [116] (Fig. 10).

Recently, Breimer et al. introduced a synthetic brain simulator for endoscopic third ventriculostomy (ETV) based on 3D printing technology [113]. The model had several advantages including low cost, portability, reusability, and lack of special maintenance. The authors believe that the trainer can reproduce the surgical procedure with realism and assist residents in developing hand-eye coordination, instrument handling, and camera skills required for ETV.

Tai et al. introduced a different neurosurgical simulator based on 3D printing technology for external ventricular drain placement. The physical trainer was designed to perform skin-to-skin external ventricular drain placement, allowing participants to practice the entire procedure [117]. The developers described that the trainer provides realistic tactile feedback and enables visualization of the trajectory of the catheter during the simulation.

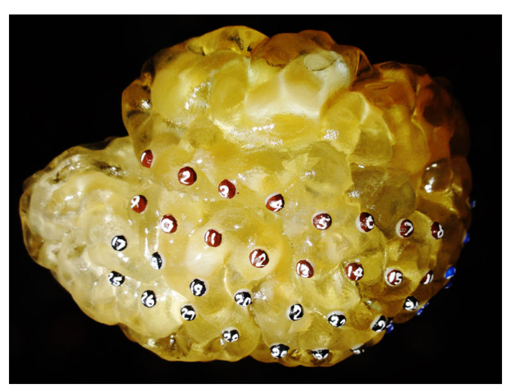

Fig. 10 Patient-specific 3D printed model of a 16-month-old boy with tuberous sclerosis and subependymal nodules. Model used for planning epilepsy surgery (figure also for consideration for the cover illustration)

Conclusion

Improvements in imaging and computer technology have led to the development of several simulation models. Procedure-based medical specialties have been encouraged by the ACGME to create accurate neurosurgical simulators to complement traditional training. Innovative trainers are commercially available, including sophisticated virtual reality systems with haptic feedback and impressive virtual imaging. Advances in 3D printing technology, allowing for high-fidelity patient-specific trainers, hold great promise for the future as a powerful tool in the development of technical skills and surgical performance.

Conflict of interest The authors report no conflict of interest.

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