Surgical Neurology International

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Review Article

Simulation and resident education in spinal neurosurgery

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Received: 12 September 14 Accepted: 07 November 14 Published: 26 February 15

This article may be cited as:
Bohm PE, Arnold PM. Simulation and resident education in spinal neurosurgery. Surg Neurol Int 2015;6:33.
Available FREE in open access from: http://www.surgicalneurologyint.com/text.asp?2015/6/1/33/152146

Abstract

Background: A host of factors have contributed to the increasing use of simulation in neurosurgical resident education. Although the number of simulation-related publications has increased exponentially over the past two decades, no studies have specifically examined the role of simulation in resident education in spinal neurosurgery.

Methods: We performed a structured search of several databases to identify articles detailing the use of simulation in spinal neurosurgery education in an attempt to catalogue potential applications for its use.

Results: A brief history of simulation in medicine is given, followed by current trends of spinal simulation utilization in residency programs. General themes from the literature are identified that are integral for implementing simulation into neurosurgical residency curriculum. Finally, various applications are reported.

Conclusion: The use of simulation in spinal neurosurgery education is not as ubiquitous in comparison to other neurosurgical subspecialties, but many promising methods of simulation are available for augmenting resident education.

Key Words: Neurosurgery, resident education, simulation, training, virtual reality

Access this article online
Website:
www.surgicalneurologyint.com
DOI:
10.4103/2152-7806.152146
Quick Response Code:

INTRODUCTION

The use of simulation in training surgical residents is an area of rapidly growing popularity and research. Several factors have favored the increasing use of surgical simulation, including mandated resident work-hour restrictions, growing demand for hospital efficiency, and a greater emphasis on patient-centered care with closer supervision by attending physicians. Additionally, there are concerns that the traditional Halstedian model of surgical mentorship may limit the efficiency of surgical skill acquisition in an era that residents are expected to master an unprecedented amount of knowledge.[6,12,40,67,68,83] Simulation allows residents to gain skills in a risk-free environment, which is especially germane in the field of neurosurgery.

The neurosurgical community recognized the potential benefits of simulation in education and has become a leader in research of this learning tool. Numerous studies have reported novel methods of simulation, and recent reviews have summarized much of this information.[2,9,34,49,75] However, the rapid development of technology and the near-exponential growth of simulation-related studies warrant current review of the literature. Furthermore, there are no studies in the current literature regarding the use of simulation for resident education specifically in spinal neurosurgery.

The purpose of this review is to provide a current overview of the use, benefits, and various applications of simulation in spinal neurosurgery.

METHODS

We performed a structured search of MEDLINE, PsycINFO, and ERIC to identify relevant literature. Various search terms were used in combination for each query, including "Spine"[Mesh], "Education"[Mesh], "Neurosurgery"[Mesh], and "Simulation." All results were screened by title and evaluated further when needed for their relation to the subject. We specifically performed some searches without specifying "Neurosurgery" in attempt to include studies from the orthopedic literature. Additionally, the PubMed "Related Citations" search capability and the reference sections of relevant articles were utilized. These searches were current as of September 2014.

History

The evolution of simulation and its eventual adoption by the medical field has a rich history and has been explored extensively elsewhere.[68,73,83] Briefly, simulation has been used for centuries in various capacities, including cadaveric dissection by early physicians (such as Galen) and military training (war games).[18,54,76] Modern simulation, however, is based on advances made in the aviation industry, with reports of flight simulation as early as 1909.[83] Simulation training continued to expand in the military and commercial industry, with applications ranging from aircraft to nuclear submarines.[5,62] Whereas the use of cadavers and animal models had long been used in surgical education, virtual reality (VR) simulation was first used in surgical education in 1987 and popularized in the early 1990s.[74,90] At that time, simulation in surgery became a field of great innovation and burgeoning research. This technology was embraced by many members of the neurosurgical community, who recognized the vast potential of simulation to revolutionize this field, where intraoperative mistakes may have dire consequences.[4,19,33,89]

Over the past 20 years, simulation has gained widespread acceptance as a tool for surgical education. Many novel modalities have been described, and the number of publications regarding simulation has grown exponentially [Figure 1]. There are three broad categories of simulation currently used in neurosurgical education: Human and animal cadaveric models, synthetic (physical) models, and VR (haptic/computerized) applications. Additionally, simulations may use a combination of these methods. Each has distinct characteristics with unique advantages and disadvantages[20,28,41,51] [Table 1]. In the field of neurosurgery, physical models and VR applications are currently available for simulation in nearly every subspecialty, including cerebrovascular, endovascular, spine, neurosurgical oncology, and pediatrics. To date, though, the majority of publications have focused on cranial and endovascular techniques. Many authors have recognized a relative paucity of research in spine surgery simulation.[29,91,95]

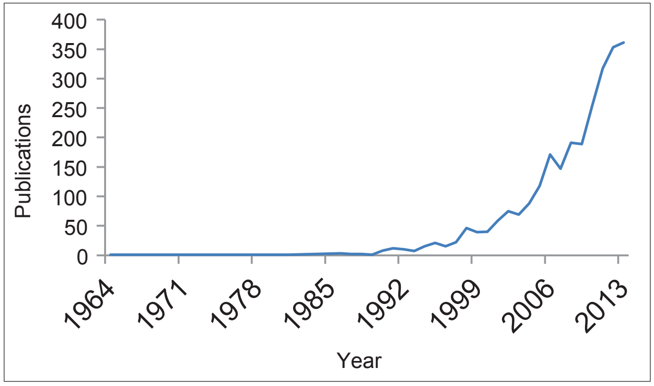

Figure 1: Number of publications regarding simulation in surgical education indexed on PubMed per year. *Results found using the following search query ("Education"[Mesh] AND simulation AND surgery). The "Results by Year" feature on PubMed was used to export the data into Microsoft Excel

Table 1: Advantages and disadvantages of various types of simulation

Type of simulation	Advantages	Disadvantages
Cadaveric (human and animal)	Accurate tissue representation, anatomic fidelity (human)	High cost, ethical concerns, need for additional staff and laboratory space, rare pathology, not reusable
Synthetic	Portable, reusable, pathology simulation possible	Poor tissue representation, sometimes not reusable
Virtual reality (VR)	Reusable, pathology simulation possible	High cost, technical maintenance, software subscriptions, haptic response still less realistic (but improving)

Current utilization in residency programs

Residents' perceptions of the role of simulation in neurosurgical education have not been well explored, but several studies examining the perceptions of residents in other specialties demonstrate that most residents have a positive attitude toward simulation in their education.[14,56,58,94] Kirkman *et al*. recently proposed a validated tool for assessing perceptions toward simulation in neurosurgery.[35] While the study was primarily focused on validation of the questionnaire, referred to as NEAT (Neurosurgical Evaluation of Attitudes towards simulation Training), they also reported that neurosurgical residents (n = 31) showed a strongly positive attitude toward simulation training.

In addition to attitudes toward simulation, other pertinent information has been reported regarding simulation in surgical training. For instance, simulation seems to offer the most benefit for junior residents, specifically in postgraduate years (PGYs) 1-3.[20,23,80,94] Senior residents have often times already acquired many of the technical skills that can be taught using simulation. One study found that junior residents reported the most benefit from simulation with cadavers, followed by physical models and then haptic/computerized simulators.[23,42] However, PGY-1 residents reportedly are least likely to be included in cadaveric simulation curriculum.[41] Interestingly, senior residents reported the most benefit from the computerized simulators, followed by cadavers and then physical models. This is possibly due to the fact that cadavers offer the opportunity to practice dissections and approaches with anatomic fidelity in the absence of pathology, a skill in which senior residents have already gained experience.

In a 2014 survey of neurosurgery residency program directors, over 90% of the 65 respondents reported using cadaveric or animal dissection as part of residency training.[41] Seventy-five percent of programs schedule between 1 and 6 training sessions for residents on an annual basis, and over half of all programs allow laboratory time for resident self-study. In these scheduled training sessions, 88.5% of programs taught spinal approaches and 80.3% taught some form of spinal instrumentation. Finally, nearly half of all respondents reported using physical or VR simulators in their resident education; 11% reported using spine simulators. Thus, the current use of physical or VR models for teaching spinal procedures appears to be quite low. A prior survey of neurosurgery residency program directors reported information regarding general attitudes toward simulation.[20] Nearly 75% of all respondents ($n = 53$) agreed that simulation could improve patient outcomes, provide an objective assessment of surgical skill, and be an effective supplement to time in the operating room. Ninety-five percent of program directors would encourage simulation use, and 75% would actually mandate the use of simulation in their programs. Nearly half (43%) expect residents to use simulation for training for 30 min to 1 h per day.

A few general themes can be inferred from the literature. First, integrating simulation into neurosurgical education should be done primarily with the residents in mind. Without careful attention to resident feedback or complete resident "buy-in," simulators will not be utilized to their potential capacity.[16] Second, intentional integration of simulation into resident education as a formalized curriculum is essential.[24,37] In order for simulation to demonstrate benefit in the field of neurosurgery as it has in the aviation industry and military efforts, it must be included in the certification process. Successful development of curricula has been described, which can be utilized in institutional-based or conference-based settings.[11,23,28] Third, a combination of different simulation modalities seems to be effective. Because of the inherent advantages and disadvantages of these different types of simulation, distinct skillsets may be gained from each experience. Furthermore, residents in different levels of training vary in which types of simulation they rank most educationally beneficial. Lastly, there are many important considerations regarding *how* residents practice on simulators. Independent and deliberate time-distributed practice allows for the most efficient acquisition of skill when using simulation for educational purposes.[34,51,53,55,61] Periodic feedback from an attending surgeon regarding simulation performance is also important for maximum benefit.[24,31,84]

Various applications of simulation in spinal neurosurgery education

The various uses of simulation in spinal neurosurgery education can be reported in several ways. For example, they can be characterized by the method of simulation used (cadaveric, physical, VR, etc.) or by the specific procedure being simulated (pedicle screw fixation, laminectomy, dural repair, etc.). For the purposes of this review, we report the various applications of simulation by the method of simulation used.

Human and animal cadaveric simulation

Cadaveric dissection has been used for millennia.[18,54] The anatomic fidelity provided by cadavers has proven to be invaluable in educating physicians and surgeons. Although over 80% of responding program directors reported using cadavers for teaching spinal approaches and instrumentation, descriptions of specific methods, procedures, and validation using cadavers in teaching spinal neurosurgery is vastly underrepresented in the literature. Most recent reports on simulation and resident education in spinal neurosurgery have focused on using sheep, calf, or deer spines.[3,32,81,86,87,91] Kalayci *et al.* described a method to teach classical discectomy skills, as the use of this procedure has decreased in prevalence due to increased morbidity.[32] In 2009, Walker *et al.* reported a novel, reproducible, and inexpensive minimally invasive spine surgery (MISS) simulator designed to teach residents important skills before application in the operating room.[91] Residents reported increased mean confidence ratings for both minimally invasive laminectomy and pedicle screw placement after working with the simulator. In 2011, Anderson reported that the University of Wisconsin had developed two spine simulation models: Dural repair and laminoplasty.[3] In the dural repair simulation, two Foley catheters are placed into the dural space and infused with saline to 90 mmHg. After a resident performs a laminectomy, a midline durotomy is made and the resident must repair it, with the quality of repair being measured by the degree of water-tight closure. This task is optimal for simulation because failure to properly close an incidental durotomy may lead to prolonged bed rest and increased hospital costs, so residents may receive little intraoperative practice with this procedure. Recently, Suslu *et al.* have detailed the use of sheep spines for training in pedicle screw fixation, lumbar microdiscectomy, and percutaneous lumbar transforaminal epidural injection.[86-88]

One of the disadvantages of using cadavers in surgical education is the lack of pathology [Table 1]. A recent report describes a method of creating tumor pathology in the cadaveric model by simply placing portions of autologous encapsulated organs (liver and spleen) into the location of the desired pathology from the opposite direction. This was used in over 70 dissections with good benefit.[13] These tumors were typically implanted in the third ventricle or sellar regions; however, this pathology simulation may have a potential application in spinal neurosurgery as well. Of note, the authors specify several important ethical concerns to be considered when using this method. Live broadcast surgery has also been used to augment resident anatomical dissection courses. Roser *et al*. report their set-up and experience of broadcasting live surgery as part of hands-on dissection courses for the cervical spine and spinal cord stimulation.[70] The authors also mention that formal informed consent for live broadcast surgery is not necessary from a regulatory standpoint, and that live broadcast surgery has been shown to create no excess risk for perioperative complications.[78] In addition to the aforementioned publications, several papers provide practical guidelines for faculty wishing to incorporate these simulation techniques using real tissue into resident education initiatives.[59,72,85]

Synthetic model simulation

Synthetic (physical) models use artificial tissue and components to provide simulation for specific procedures. Manikins like Resusci Annie and SIM1, used to teach cardiopulmonary resuscitation and airway management, were popularized in the 1960s and are prime examples of rudimentary synthetic simulation.[83] Many designs and uses of synthetic spine surgery simulators have added to this rapidly expanding set of literature over the past several years.[25,52,65,79,80] This is due in part to the advent of three-dimensional (3D) printing and its increasing use in the medical field, as skulls and vertebrae can now be printed instantly using patient-specific computed tomography (CT) scans.[66,93]

The department of neurosurgery at the University of Illinois, in conjunction with the mechanical engineering department of Bradley University, developed a synthetic simulator for pediatric lumbar spine pathologies, including tethered cord syndrome and open neural tube defects.[52] Using 3D printing, a pediatric lumbar spine and sacrum were created. The simulator was designed to incorporate different types of material that would mimic the tensile properties of actual tissue. In addition, the simulator is modular in nature to allow for the replacement of certain layers that are eventually disrupted and destroyed with repetition. The simulator realistically portrays the desired pathologies for residents, and the authors report several specific challenges and variables to be considered in the development of any future simulators. A novel synthetic simulator has also been developed for anterior cervical discectomy and fusion (ACDF).[65] After identifying a lack of spine simulator devices, the Congress of Neurological Surgeons (CNS) developed the ACDF simulator as part of an educational curriculum for the 2012 annual meeting. The simulator is comprised of a mix of compounds in the silicone family in an attempt to emulate the tissue in anterior cervical region, and a polyurethane mix for vertebrae, ligaments, and disks. Actual anterior cervical screws and plates were used to perform the procedure, and the spine portion of the simulator can be removed and replaced after each use. Simulating this procedure is beneficial as ACDF is essentially a single-surgeon procedure. A synthetic model for simulating dural repair has also been reported.[25] This synthetic model was adapted from the cadaveric dural repair model described in this paper previously and uses the same basic concept.[3] A dural substitute (DURA-GUARD, Synovis Surgical, St. Paul, Minnesota) was used to portray accurate tissue representation. In addition to these synthetic simulators, recent efforts have been made to develop simulators capable of reproducing several pathologic conditions including scoliosis, degenerative disease, spinal stenosis, and spinal deformity, although results have not been yet reported.[30]

Virtual reality simulation

The use of VR in neurosurgery education is intriguing and has definite potential to revolutionize the training of surgeons. As frontiers expand in computing, graphics, modeling, and haptic (tactile feedback) technology, VR will almost certainly become a central component of resident education in the future. Currently, however, VR simulation is in its infancy. Nevertheless, VR simulation in its current state has been shown to provide benefit in training neurosurgeons.

The earliest VR spine simulators were developed around the turn of this century.[15,38,43,45,63] Since then, several VR simulators have been commercially developed. The simulator with perhaps the most research validation in the literature is known as ImmersiveTouch® (Immersive Touch, Inc., Chicago, Illinois).[1,22,47,48] At present, the following spinal procedures can be simulated by this simulator: Percutaneous lumbar puncture, Jamshidi needle biopsy, thoracic and lumbar pedicle screw placement, percutaneous spinal fixation, and vertebroplasty. According to the company website, several other procedures are under development, including anterior cervical discectomy, lateral mass fixation, lumbar laminectomy, lumbar microdiscectomy, C1-2 transarticular screw fixation, pelvic fixation, and minimally invasive direct lateral interbody fusion (DLIF). A simulator called the Dextroscope® (Volume Interactions Pte, Ltd., Singapore) has also been evaluated in the literature.[17,26,39] This system focuses on preoperative planning, allowing surgeons to visualize patient-specific anatomy in a 3D environment through the creation of a virtual surgical field. Although bone drilling and aneurysm clipping procedures are available on the Dextroscope®, its primary uses have been neuroanatomical instruction and preoperative planning.[49] Another VR simulator that can be used in spinal neurosurgery is the Surgical Rehearsal Platform (SRP) (Surgical Theater, LLC., Mayfield Village, Ohio). This system models patient-specific Digital Imaging and Communications in Medicine (DICOM) images into an interactive 3D setting for preoperative planning and procedure rehearsal. Like most VR simulators, the initial focus has been on cranial procedures; however, pedicle screws have been modeled for practicing trajectory and placement prior to surgery. Additionally, the company is currently partnered with many institutions and looking to further develop the simulator's spinal procedure capabilities.

In addition to these commercially available simulators, several other VR spine simulators have been reported in the literature.[36,46,49,60,64,71] Many of these applications attempt to model pedicle screw insertion, as a recent review of pedicle screw techniques and training has explored.[36,50,60,64] Simulation for learning pedicle screw placement is optimal as misplacement can cause damage to neighboring neural and vascular structures, and a working knowledge of complex 3D anatomy is necessary for proper screw alignment and trajectory. Furthermore, a retrospective review showed a 15% misplacement rate among neurosurgical residents inserting thoracic pedicle screws.[92] Simulated pedicle screw placement can aid residents in mastering this complex procedure. Rush *et al*. described a computerized simulator for sacroiliac screw insertion.[71] Users may visualize a 3D reconstruction of the pelvis, use K-wires to appropriately size screws, and insert the screws. Liu *et al*. also utilized 3D reconstruction technology to model the craniocervical junction, allowing users to simulate the trans-oral and posterior-lateral approaches to the superior cervical spine.[46] Malone *et al*., authors of a 2010 review of VR simulation in neurosurgery, have begun to develop a simulator for instrumented lumbar fixation, which includes pedicle cannulation, internal pedicle fixation, and screw insertion.[49]

Mixed simulation

In addition to the three primary types of simulation, the use of mixed simulation in spinal neurosurgery training has been described.[7,10,27,29] These simulators combine at least two types of simulation in order to take advantage of each respective strength. Harrop *et al*. developed a novel cervical spine simulator for teaching posterior foraminotomy and laminectomy as part of the CNS initiative described above.[29] Through collaboration with Phacon Corporation (Leipzig, Germany), the authors used 3D printing, special tools that could be tracked via a standard webcam for intraoperative navigation, and pressure sensors to create the final simulator that was used at the 2012 CNS annual meeting. The simulator was received well by residents, but the authors noted that cost of the spine model, which can only be used once, is a significant limiting factor for distribution of this simulator to a wider audience. A novel simulator for anterior cervical disc replacement has also been described, focusing on the nerve decompression (rasping) portion of the procedure.[27] Briefly, a motion tracking system known as VICON is used to "map" the surgical instruments and spine model to a virtual environment. The user visualizes the field through stereoscopic binoculars while manipulating the physical model. This simulator was deemed effective by five surgeons but required a significant investment for development like many VR/mixed simulators ($250,000). Two other mixed simulators have been developed for procedures involving the lumbar spine. In the past year, Chitale *et al*. reported a simulator for minimally invasive percutaneous pedicle screw placement that utilized fluoroscopic and CT-navigated components.[10] Lastly, Bova *et al*. describe their experience with mixed simulation and spinal instrumentation in detail.[7] In addition to describing the development of their simulator, they stress the importance of taking steps to emulate the environment of the operating room during simulation, including surgical drapes, C-arm footswitches, and overlying soft tissues in the physical model. These techniques combine the challenges of microsurgical techniques and the accurate placement of instrumentation in complex anatomy.

DISCUSSION

The use of simulation in neurosurgical education is rapidly increasing. In addition to resident education, simulation has been used to explore the effects of postcall fatigue.[21] Preliminary research has explored the feasibility of using simulation to screen medical students applying to surgical residencies,[69,77] as surgical applicants have been shown to not self-select for manual dexterity.[44,57] Finally, ongoing research has explored simulation as a metric for surgical skill,[82,95] and many predict that simulation will eventually be a required portion of oral board examinations of the American Board of Neurological Surgery.[8,20]

Although the use of simulation in spinal neurosurgery has been considered to be lagging behind other neurosurgical subspecialties,[29,91,95] this review has shown that a wealth of spine simulators have recently been developed for use in neurosurgical education. As the benefits of simulation in resident education continue to be reported, an increasing number of institutions will begin to utilize these training techniques. In addition to mandated resident work-hour restrictions, growing demand for hospital efficiency, and a greater emphasis on patient-centered care with closer supervision by attending physicians, other factors may encourage the adoption of simulation as part of resident curriculum, such as the growing popularity of 3D printing or an increased demand from residents.

However, several issues may impede the progress of simulation in neurosurgical education. One of these was perhaps best summarized by Mattei *et al*., "It seems clear that isolated attempts from different residency programs to develop and implement their own simulation modules for different neurosurgical tasks would result in a very high collective economic burden and probably only some few successful results, rendering such individualistic approaches not cost-effective."[52] With this in mind, future studies should evaluate various simulation approaches in neurosurgical education and communicate what has worked and what has not, paying careful attention to report reproducibility, practical materials and methods instructions, 3D printing instructions, etc., Journals may consider making this specific information available in online supplements and/or videos. In a recent systematic review, Kirkman *et al*. encouraged investigators to "improve study design and reporting and provide long-term follow-up data on simulated and/or patient outcomes."[34] Cost may be another factor that may impede the utilization of simulation in resident education. While many of the simulators described in this review can be reproduced inexpensively, several simulators (mainly VR and mixed simulators) would be a considerable investment for residency programs, costing hundreds of thousands of U.S. dollars. Gasco *et al*. reported costs of implementing an integrated residency curriculum,[23] providing pertinent information for any program with the desire to integrate simulation into their resident education. However, there is a paucity of research concerning the cost–benefit relationship of simulation use in neurosurgical residency training. Despite these potential obstacles, the future of simulation in neurosurgical education remains an exciting prospect.

CONCLUSION

Several factors have led to an increasing use of simulation in neurosurgical education, and this has been a rapidly growing area of research. Spinal neurosurgery has lagged behind other subspecialties in terms of available simulators, but a wealth of recent publications have described a variety of educational options for training residents in spinal neurosurgery. Although obviously not a substitute for live surgical training, simulation will undoubtedly become a central component in resident education for teaching necessary surgical skills in a risk-free environment.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Karen K. Anderson, B.S., for assistance with manuscript editing and preparation. This work was supported by a CTSA grant from NCATS awarded to the University of Kansas Medical Center for Frontiers: The Heartland Institute for Clinical and Translational Research # TL1TR000120. The contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIH or NCATS.

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