Endovascular Surgical Neuroradiology Simulation

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Introduction

Surgical training is currently undergoing a paradigm shift from traditional apprenticeship-based training to increased use of simulation-based training [1]. This has been driven, in part, by concerns for patient safety issues, work hour restrictions, and limited training opportunities under current apprenticeship models [1]. Regardless of method, the acquisition of efficient, reliable, and safely performed complex psychomotor skills, in addition to surgical judgment to contend with variable anatomy, pathology, and potential complications, is paramount. Given the increasing public interest in physician qualifications, programs such as Maintenance of Certification have been implemented to ensure high standards of medical practice with the goal of improving care, increasing patient safety, and providing better cost-benefit ratios. The assessment of key competencies and procedural skills is challenging, and a written examination may be insufficient in a surgical field as a marker for overall competence [2].

Development of virtual reality simulation-based surgical skills has demonstrated improved performance and transfer of newfound skills in the operating room across multiple specialties [3–7]. In the field of laparoscopic surgery, standardized basic simulated programs such as the Fundamentals of Laparoscopic Surgery has been incorporated into training curricula and is now a prerequisite for certification with the American Board of Surgery [7, 8]. Many surgical specialties have developed unique simulators to suit specialty-specific techniques that are required in each respective surgical training including, but not limited to, laparoscopy, arthroscopy, bronchoscopy, gastrointestinal, genitourinary, gynecologic, temporal bone surgery, robotic surgery, and endovascular surgery [1, 4, 6, 9, 10].

This chapter will focus on the use of simulation in neuroendovascular surgery. We will first review simulator-based training in endovascular surgery, then discuss modern neuroendovascular simulation devices and the available literature on neuroendovascular simulation and procedural performance.

Electronic supplementary material: The online version of this chapter https://doi.org/10.1007/978-3-319-75583-0_6 contains supplementary material, which is available to authorized users.

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A. Alaraj (ed.), *Comprehensive Healthcare Simulation: Neurosurgery*, Comprehensive Healthcare Simulation, https://doi.org/10.1007/978-3-319-75583-0_6

Simulation-Based Training in Endovascular Surgery

Modern medicine has increasingly evolved toward minimally invasive procedures, and the mastery of endovascular techniques has become crucial in multiple specialties [11]. Catheter-based procedures are widely utilized in endovascular surgery and interventional radiology and are employed for diagnosis as well as therapy. These procedures demand a specialized skill set for successful navigation through three-dimensional vascular trees using two-dimensional on-screen feedback. It can be challenging for trainees to acquire this surgical skill set in the current apprenticeship model, as interventional procedures often allow for just one surgeon at a time [11]. Currently, training is carried out primarily in the patient care setting, occasionally with increased risk to patient safety [12]. For this purpose, virtual reality simulators have been developed to assist with endovascular training.

The unique properties of endovascular procedures provide both a blessing and curse for simulation. On one hand, replicating endovascular procedures on a simulator is relatively simple. Proceduralists never actually "see" the coils as they leave the catheter or the actual movement of the catheter or wire, just image representations on biplanar fluoroscopy. As such, simulators must merely capture catheters and wire movements and then produce a visual representation on a screen that mimics fluoroscopy. These factors therefore make simulation of angiographic cases much more simplistic than open surgical procedures, because all that is needed is wire and catheter input. On the other hand, because endovascular skills in real clinical practice demand mastery of subtle hand motions and understanding load on devices and fluid physiology, the haptics of capturing subtle hand movements and the effect of blood hemodynamic factors on simulated device responsiveness must be so much more realistic to make simulation effective and realistic. This means that developing a generic endovascular simulator is relatively straightforward, but designing a realistic one may actually be incredibly complex. Fortunately, as technology advances, simulators are becoming more and more realistic.

Training modules such as the vascular interventional system trainer [13] developed in Sweden have been demonstrated to significantly improve operator outcomes in the context of lower extremity occlusive disease, cardiac disease, and carotid disease [11, 14–16]. In a prospective observational cohort study, Lee et al. enrolled 41 medical students in an 8-week elective vascular surgery course where they were trained in renal artery stenting using a high-fidelity endovascular simulator [17]. There was a statistically significant improvement in procedure time, accuracy, and overall performance when comparing pre- and post-training sessions [17]. Similarly, Van Herzeele et al. demonstrated a statistically significant improvement in the performance of 11 experienced endovascular interventionalists after attending a 2-day course for carotid artery stenting using endovascular simulators [18]. Improvement in performance can be seen in total procedural times, contrast use, cannulation time, and target accuracy [11]. These and other studies indicate that training with endovascular simulation can improve the performance of novice as well as experienced interventionalists [19, 20].

See et al. performed a meta-analysis of the endovascular simulation literature and found 23 trials showing statistically significant improvements in procedure time, fluoroscopy time, and contrast volume [21]. Five trials were patient-specific procedure rehearsals, demonstrating that simulation significantly affected the fluoroscopy angle and improved performance metrics, and three were randomized controlled trials revealing both overall and procedure-specific improvements after endovascular simulator training, supporting the idea that there is a beneficial role of simulation in endovascular training [21].

Neuroendovascular Simulators

There are two currently available approaches in neuroendovascular simulation: computerized virtual reality simulators and silicone vascular models, with or without a circulation pump. VR simulators are capable of recording the surgeons actions, translating this into a digital performance assessment with quantitative evaluation [2]. On the silicone vascular flow model, the trainee is able to use the material in its dedicated "wet" environment allowing practice with every step of a procedure.

Flow Models

The Replicator (Vascular Simulations, Stoneybrook, NY; Fig. 6.1) is a replica of the human arterial system including a functional left side of the heart. This advanced flow model replicates individual patients' anatomy and pathology, which can be used to perform and practice neuroendovascular procedures prior to clinical treatment. It duplicates the cardiac cycle with a functional left atrium and ventricle, and "blood flow" passes through a silicone aorta with compliance that recreates the waveforms of a human aorta. The cervical vessels arising from the aortic arch and cerebral vasculature are made from imaging studies of the actual patient, and their pathology, such as an intracranial aneurysm, can be recreated. Additional modules are underdevelopment, including stroke, carotid stenosis, cerebral arteriovenous malformations, abdominal aortic aneurysms, and aortic and mitral stenosis.

Less sophisticated flow models also exist (Video 6.1), with silicone circuits filled with saline with various pathologies (most commonly, cerebral aneurysms), which allow for use under direct vision, or fluoroscopy, to practice using different technologies such as coils, stents, flow diverters, and embolic agents (Fig. 6.2). These have the benefit of being easily portable and are fairly reasonable and are often used to introduce new interventional products to interventionalists, who can practice the deployment of new stents or compare different coils head-to-head. They do have the drawback of absent pulsatile flow, and the absence of catheter stability from the usual femoral arterial access spanning the vascular tree, with redundant catheter eliminating the typical one-to-one tactile feedback that is necessary for precise movement deployment. Arthur et al. observed a shortened learning curve with use of advanced techniques in a high-fidelity simulation environment such as the Replicator, without compromising patient safety [22, 23].

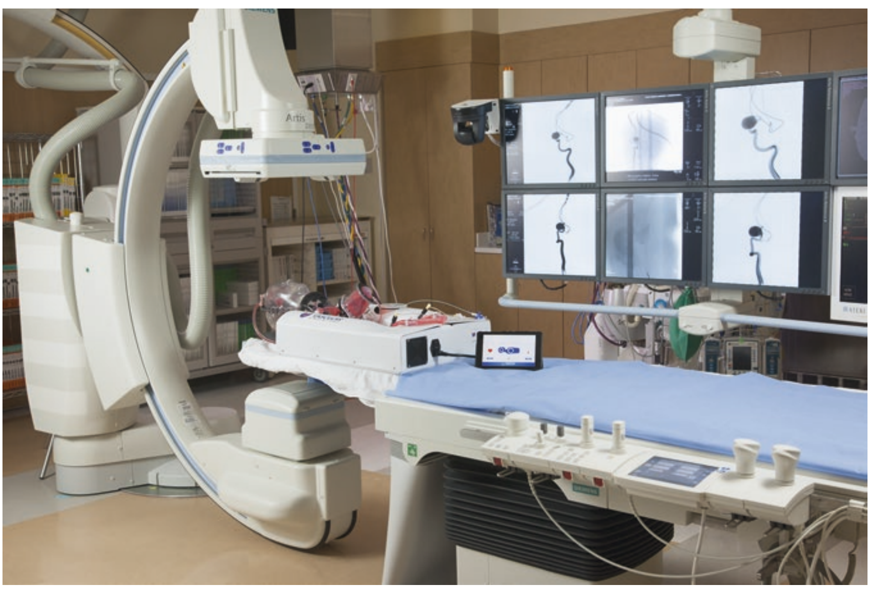

Fig. 6.1 The Replicator simulator (with permission from Vascular Simulations, LLC)

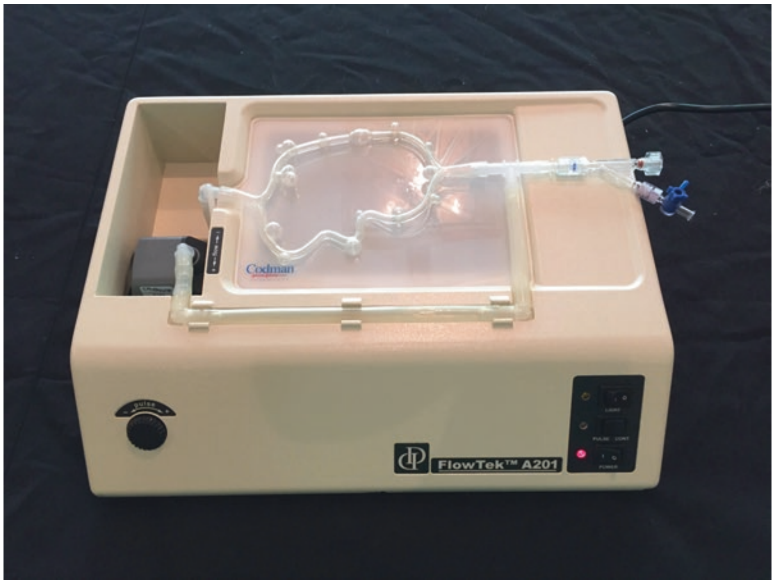

Fig. 6.2 A silicone flow model device with saline pump and simulated aneurysms

VIST- C: Vascular Intervention Systems Training (Mentice, Goteborg, Sweden)

The VIST-C system (Mentice, Goteborg, Sweden) is an endovascular interventional simulator that has a wide variety of applications, from femoral, iliac, aortic, renal, carotid, coronary, to intracerebral vessel simulation (Fig. 6.3). It is a portable, high-fidelity endovascular simulator (Video 6.1). This system makes use of actual endovascular catheters and wires engaged along internal tracking wheels that are introduced through a port, capturing fine movements of the catheter in all planes [24]. Virtual contrast is simulated by the injection of air by a syringe, and advanced haptics provide sensory feedback using force feedback technology [25]. There are a wide variety of training scenarios with actual devices and equipment used in clinical practice to challenge the learner's technical skills, clinical decision-making abilities, and procedural proficiency.

ANGIO Mentor: Simbionix (3D Systems, Littleton, CO)

The Simbionix ANGIO Mentor system (3D Systems, Littleton, CO) provides an interactive biplanar fluoroscopic display for both diagnostic and interventional case scenarios. The system is able to incorporate a wide variety of sheaths, diagnostic catheters, and guide wires and measure their unique mechanical properties in constructing the simulation [26]. The system uses the mechanistic properties of the catheters and wire such as shear and Young's modulus, to measure the wire manipulations by tracking horizontal translation and rolls at a fixed position, and translates this visually onto the screen [26]. Vessels exert varying forces to keep the catheter intraluminally, and software calculates the collision forces of the catheter into the vessel wall [26]. This combined information allows the system to simulate the position of the catheter in the vessel by calculating values such as angulation, friction, and forward loading, for high-end haptic feedback, which realistically mimics actual endovascular interventions.

The system features over 23 different endovascular procedures and 158 patient scenarios and spans multiple disciplines, including interventional cardiology, interventional radiology, vascular surgery, cardiothoracic surgery, electrophysiology, interventional neuroradiology, trauma, and neurosurgery. The PROcedure Rehearsal Studio (3D Systems, Littleton, CO) can

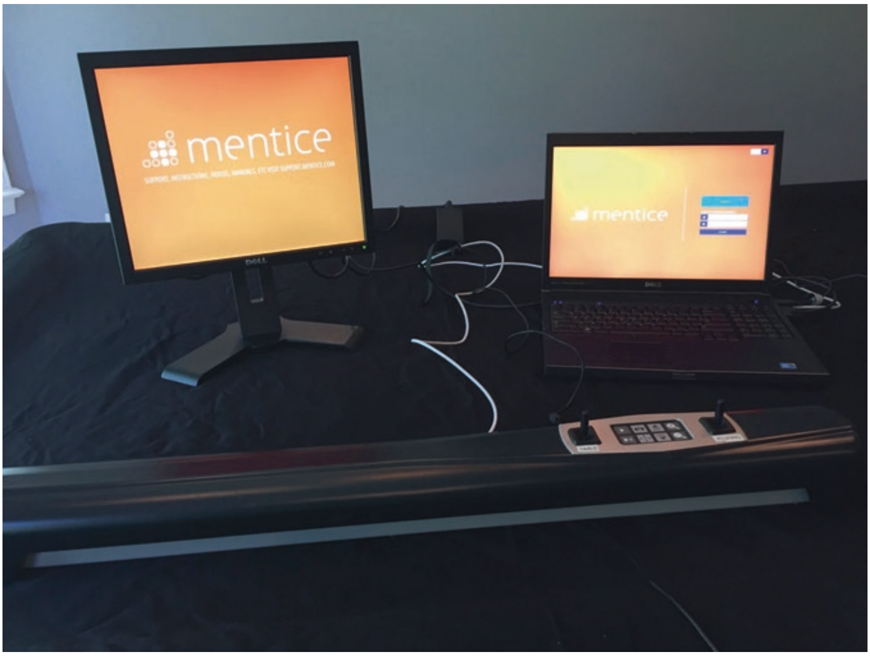

Fig. 6.3 The Mentice simulator with simulated table and foot pedal controls (not shown)

be used to prepare for upcoming interventions creation of a patient-specific 3D model based on scanned images. This 3D model can be exported to a virtual simulation environment or physically printed by 3D printers, for the purpose of simulating, analyzing, and evaluating surgical treatment options.

Compass: Medical Simulation Corporation (Medical Simulation Corporation, Denver, CO)

The Compass (Medical Simulation Corporation, Denver, CO) is a more portable endovascular simulator. It fits into a single case similar to a rolling suitcase and can be checked as luggage on an airplane. It can be set up within minutes and used on a conventional table for single use on a high-fidelity screen or projected to a large screen display for large group training. Tactile feedback is provided with anatomical variations and upon device deployment. A tablet is used to control elements such as contrast injection or C-arm movement.

Endovascular Simulation in Neurosurgical Training

Endovascular techniques are a skill set entirely separate from that of “open” neurosurgical technique. While traditional neurosurgical residency focuses on the use of two-hand instrument and suction techniques under direct visualization (and often with the aid of magnification), endovascular procedures involve the subtle manipulation of wire and catheter with the results visualized on a monitor. While both techniques require considerable repetition to master, importantly mastery of endovascular techniques is not predicated on proficiency in open neurosurgical techniques and vice versa. While this fact seems obvious as interventional neuroradiologists and neurologists perform endovascular surgeries, it represents an important distinction in neurosurgical training. Importantly, the lack of prerequisite skills means that trainees may learn and practice these skills at any point in their training. This is unlike many other specializations within neurosurgery. For example, consider neurosurgery residents that would like to complete an open cerebrovascular microsurgery fellowship to acquire mastery in vascular microneurosurgery. Before being a suitable fellow where surgical nuance can be learned, applicants must first master general neurosurgery to provide a foundation on which new skills can be acquired. Therefore, in-folded fellowships where inexperienced residents attempt to learn complex microneurosurgery are not feasible. However, endovascular skills do not require a foundation of neurosurgical skill and can therefore be learned at any point during neurosurgery residency training. The fact that medical students, residents, and even fully trained attending neurosurgeons may potentially be equally equipped to acquire endovascular skills means that there is a potential role for endovascular simulator learning across the entire training spectrum. This may widen the applicability of an endovascular simulation and may maximize yield for departments looking to employ simulation in their residency training program.

While there is increasing utility of simulation in residency training in interventional radiology and general surgery, simulation in neurosurgical training is lagging slightly behind that of other specialties [24]. However, pilot projects of endovascular simulation show excellent utility for this training modality [24]. With the primary objective of providing education in the fundamental principles of angiography, anatomy identification, catheter selection, fundamentals of catheter and wire interaction, reducing radiation exposure, and basic angiography, Fargen et al. demonstrated that a hands-on simulator course (VIST-C, Mentice, Goteborg, Sweden) for neurosurgery residents with no prior experience increases performance and trainee knowledge, creating a viable means to train residents early on [24]. Pre- and post-training tests, including general principles of angiographic anatomy, procedures, and indications, as well as objective data including fluoroscopy time, time to target vessel cannulation, and volume of contrast used, all showed a statistically significant improvement [24].

Another neurosurgical pilot study by Spiotta et al. used the Simbionix system (Simbionix USA Crop, Cleveland, OH) to assess the utility of endovascular simulation in neurosurgical residents and fellows with varied experience [26]. Each participant was asked the number of angiograms performed and their knowledge of the aortic and cervical vascular anatomy, along with their level of comfort on catheter selection and technique [26]. Residents with limited prior experience were given a short didactic presentation regarding basic anatomy of the aorta and its branches, properties, and geometry of diagnostic catheter and guide wires, basic technique of crossing the arch, and selective catheterization [26]. The residents reported a paucity of exposure to cerebral angiograms (50% having never observed one, 2 with <5 observed, and 1 with >10 observed) [26]. All fellows had performed more than 100 cases [26]. Regardless of prior exposure to angiography, all participants, both residents and fellows, showed an improvement in the trials as demonstrated by fluoroscopy times [26]. There were no serious simulated complications during the training session, although residents with little prior exposure were noted to perform occasional "dangerous" maneuvers, which were corrected with real-time instruction [26].

A similar study format was used to assess training residents in more complex aortic arch anatomy using a secondary curve catheter [27]. The training protocol started with a 5-min didactic session covering basic and complex aortic arch anatomy using a primary and secondary curve catheter and consisted of five trials with all participants showing a statistically significant improvement in overall time required for selective catheterization using a Simmons II catheter [27].

Building off of these pilot studies, a 120-min simulator-based training course was performed at two subsequent Congress of Neurological Surgeons (CNS) annual meetings [24]. Precourse written and simulator skills assessments were performed in 37 neurosurgical trainees, followed by instructor-guided training on an endovascular simulator. Post-course written and simulator practical assessments were then performed. Posttest written scores were significantly higher than pretest scores ($p < 0.001$), and instructor assessments of practical posttest scores of participants were significantly higher than pretest practical scores for both the CNS 2011 and CNS 2012 groups ($P < 0.001$), again indicating that simulation may be an effective method of teaching certain neuroendovascular skills [22].

Ernst et al. assessed key competencies and analyzed associations between the clinical experience, knowledge, and technical skill [2, 28]. All participants were European interventionalists ($N = 26$) who performed a middle cerebral artery (MCA) M1 segment thrombectomy for acute stroke and embolized a posterior communicating artery aneurysm on the ANGIO Mentor (3D Solutions,) after a brief didactic session. The Replicator (Vascular Simulations, Stony Brook NY) was used for embolization of a MCA bifurcation aneurysm with an intra-saccular flow disrupter (WEBTM Aneurysm Embolization System, Sequent, California) [28].

This study provides an example of a curriculum that reasonably and cost-effectively assesses certain competencies of a neuroendovascular surgeon in terms of theoretical knowledge and practical skills. Time of work experience does not guarantee clinical judgment or expertise; however, there are significant associations between theoretical knowledge and practical skills [2]. Moreover, technical knowledge (i.e., material and techniques) does seem to be associated with technical skill in aneurysm coiling and thrombectomy [2]. The assessment of procedural skills by the use of endovascular simulators has proven to be a feasible approach to yield objective data for evaluating technical competency [2].

Benefits and Limitations

Neuroendovascular surgery is now a clear component of neurosurgical residency training. Recently, there has been increasing emphasis placed upon inclusion of neurointerventional surgical skills within the core neurosurgical competencies, manifested by an increase in the Residency Review Committee case minimums and focus on angiographic skills and knowledge in Intern Boot camps and the written and oral board examinations. Therefore it is important that resident training programs incorporate new methods of educating trainees in neuroendovascular surgery while being compliant to work hour restrictions and not sacrificing training in other areas of neurosurgery [24].

Use of simulation in endovascular training has risen sharply, and technological advances in simulation now more closely resemble real clinical scenarios [24, 29, 30]. New devices with augmented reality simulation, combine simulation with real-world surgical devices, provide haptic feedback and with close resemblance to actual endovascular surgery [24]. Additionally, systems can now recreate actual patient anatomy and pathology, with can be used to size devices and practice treatment configurations prior to actual patient treatment. The literature demonstrates a correlation between technical skill on a simulator and clinical endovascular experience [19, 31–33], suggesting that currently available simulators mimic clinical conditions closely enough to translate into improved clinical skill [33]. Furthermore, there is data that shows even skilled interventionalists have continued benefit from simulation courses [24].

One of the greatest benefits of simulation is repetitive practice in a risk free environment. Learning of sequential steps, with the ability to repeat after correction of any mistake, is a key component to successful technical skill. Simulation allows for education without risk to patient safety, cost of medical equipment, or lab costs and time constraints. This type of learning environment is both beneficial and efficient. Simulators have several other advantages, in that they do not require radiation dose and are customizable on a case-by-case basis. Similar to other disciplines, there is a strong suggestion that skills acquired on the simulator might be transferable to the real patients in the angiography suite [2, 26, 34, 35].

However, there remain significant limitations to simulation-based training. Skills such as material preparation outside the patient cannot be trained and assessed by simulators [2]. Availability and cost remain large limitations, and to date, the haptic feedback, while significantly improved from previous generations of simulators, is still not exactly that of real-world experience. Importantly, electronic simulators do not yet have a means of adequately simulating a fluid medium that incorporates blood stasis, contrast injection, or flushing. A key skill set in endovascular technique, particularly for learners, is the prevention of air or clot embolism. Inadvertent injection of air or stagnation of blood in a catheter with resultant embolism may have dire consequences to patients. Focus on perfect technique in the presence of a hazardous fluid medium is an integral component of learning neurointerventional techniques. Unfortunately, every electronic simulator does not yet have the capability to teach learners this critical skill set. Additionally, because the simulation setting is a risk free environment and often goes unsupervised by faculty, poor technique may fail to generate real clinical consequence and may foster poor habits if no proper feedback is provided to the trainee [24].

The Future

Future studies are needed to confirm the efficacy of simulation in endovascular surgical training and to probe whether simulation is a useful adjunct to traditional training in the endovascular lab. Furthermore, research is needed to validate whether skills acquired on the simulator are transferrable to the clinical setting, and if simulator training actually improves safety and quality of patient care. The accuracy of the simulator is of utmost importance for quality training to take place with the use of neurosimulation platforms. A further step from just using the simulator as a training module is to use the simulator to "practice" difficult cases before the actual procedure. The high-fidelity simulation platform would be ideal for a "trial" treatment of many vascular conditions to assess the quality of the planned procedure; however, one must keep in mind that this is under the assumption that the simulator is an accurate depiction of in vivo conditions. It is an exciting time for neurosimulation with many more developments to come that would further advance endovascular treatment of neurovascular conditions.

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