Cerebral Aneurysm Clipping Surgery Simulation Using Patient-specific 3D Printing and Silicone Casting

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Abbreviations:
\begin{itemize}
\item 3D: three dimensional
\item ABS: acrylonitrile butadiene styrene
\item CT: computed tomography
\item MRI: magnetic resonance imaging
\end{itemize}
Abstract

Background: Neurosurgery simulator development is growing as practitioners recognize the need for improved instructional and rehearsal platforms to improve procedural skills and patient care. In addition, changes in practice patterns have decreased the volume of specific cases, such as aneurysm clippings, which reduces the opportunity for operating room experience.

Objective: The authors developed a hands-on, dimensionally accurate model for aneurysm clipping using patient-derived anatomical data and 3D printing. Design of the model focused on reproducibility as well as adaptability to new patient geometry.

Methods: A modular, reproducible, and patient-derived medical simulacrum was developed for medical learners to practice aneurysmal clipping procedures. Various forms of 3D printing were utilized to develop a geometrically an accurate cranium and vascular tree featuring nine patient derived aneurysms. 3D printing in conjunction with elastomeric casting was leveraged to achieve a patient-derived brain model with tactile properties not yet available from commercial printing technology. An educational pilot study was performed to gauge simulation efficacy.

Results: Through the novel manufacturing process, a patient derived simulacrum was developed for neurovascular surgical simulation. A follow-up qualitative study suggests simulacrum potential to enhance current educational programs; assessments support the efficacy of the simulacrum.

Conclusions: The proposed aneurysm clipping simulator can improve learning experiences in surgical environment. 3D printing and elastomeric casting can produce patient-derived models for a dynamic learning environment that add value to surgical training and/or preparation.
Introduction

Procedural surgical training is traditionally introduced to medical students via cadaveric training prior to clinical experience during residency training \(^1^2\). However, the use of both cadavers and facilities for surgical training are increasingly cost-prohibitive \(^3\). Further, in specialized surgical education, such as neurovascular training, cadavers with specific lesions or diseases are limited, which reduces opportunities for specific surgical technique development \(^3\). One solution to address the rising costs and limited availability of cadavers is to use medical simulators for procedural training to enhance the learning of cerebral anatomy and pathologies, basic principles of tissue handling and manipulation with regards to aneurysm clipping, and development of microsurgical dexterity.

Medical simulations enhance “learning of higher cognitive, psychomotor and affective skills” through interaction with a tissue, organ, organ system, and/or whole body analogues \(^4\). Simulation, when effective, aids in a learner’s development of procedural knowledge. Procedural knowledge is acquired through the engagement of cognitive and psychomotor functions; that is, the performance of a procedure, even in a simulated media, translates to the development of procedural skills \(^4\). Through simulation, learners reconcile content knowledge, learned from textbooks or lectures, with physical processes and surgical techniques \(^5\).

The use of simulation as a surgical training modality has been thoroughly explored, and the advantages of simulation are well established \(^6^10\). A recent survey of neurosurgery residency program directors noted that most believed simulators are of benefit in residency training \(^11\). In fact, the Accreditation Council for Graduate Medical Education now requires simulation-based training for general surgery residencies \(^12\). By providing an educational environment that is independent of the risks of patient care, simulators enable learners to make errors in decision-making and technique without catastrophically negative consequences \(^9^13\).
The inherent technical challenges and high risks associated with open vascular surgery make simulation a particularly appealing option for education. Further, in the case of cerebral aneurysms, the benefits of simulation are particularly valuable given the declining frequency with which open aneurysm surgery is incorporated into neurosurgical residency training. Simulators for aneurysm surgeries have previously been developed; however, improvements in material properties for multiple tissue representations can increase the realism and efficacy of simulation. A “life-like” simulacra, the physical model used in educational simulation, should include realistic anatomical structures, material properties, and numerous aneurysmal geometries (simulacrum is the physical model used in a simulation, irrespective of the curricula or content of the simulation). The small size, tissue complexity, and morphological complexity of the neurovasculature and surrounding environment make simulacrum development challenging. The remainder of this paper addresses the development of a simulacrum for a specialized neurovascular surgery: cerebral aneurysm clipping.

The prevalence of cerebral aneurysms is suspected to be as high as 5% of the US population. Aneurysmal rupture can lead to devastating consequences with a mortality rate as high as 45%. Endovascular interventions have outpaced surgical methods involving craniotomy and aneurysmal clipping. However, Bakker et al. suggest that endovascular coiling has not produced better longitudinal outcomes. In fact, some studies suggest that surgical clipping is the preferred method for specific aneurysms, depending on location, size, and lesion morphology. Consensus suggests that expertise in both surgery and endovascular intervention are necessary for optimal care of aneurysm patients. Despite the persistent need for aneurysm clipping, the reduced frequency and the high risks associated with open neurovascular surgery, neurosurgical residents and fellows have fewer opportunities to experience and learn from surgeries. A medical simulacrum with appropriate tactile feedback can address this deficit by providing learners with a risk-free environment within which to refine surgical skills.
Accordingly, the authors developed an aneurysm clipping simulacrum leveraging three-dimensional (3D) printing technologies in conjunction with silicone casting techniques. The goal of the simulacrum was to teach neurosurgical residents and fellows how to clip aneurysms effectively. Toward that end, three cognitive objectives for the residents were identified to be addressed in the simulacrum: 1) develop an understanding of the basic three-dimensional anatomy of the cerebral vasculature, 2) develop an accurate awareness of the surgical view via the standard cranial approaches, and 3) gain familiarity with the instruments and methods used to apply a neurosurgical clip. The proposed simulacrum features the integration of a multi-patient-derived vascular model that is responsive to clipping, a skull model that behaves realistically both during and after craniotomy, and a brain model with appropriate turgor and recoil to recreate the surgical experience.

**Material and Methods**

**Vascular Model:**
The vascular computational model was synthesized from nine patient datasets. CT-angiography data sets were imported into Mimics (Materialise, Lueven, Belgium), a medical reconstruction software suite. Segmentation, the process of portioning an image into parts, was performed to isolate the aneurysmal and parent vessel geometries as binary masks. The masks were reconstructed to create computational 3D surface meshes. The aneurysm meshes were imported into Geomagics (3DSystems, Rock Hill, SC, USA), an engineering software suite, where the nine reconstructions were synthesized into a single Circle of Willis computational model as shown in Figure 1A. 3D printing is feasible for branches as small as 1 mm in diameter. The vessels that met this size threshold included the anterior choroidal artery, the recurrent artery of Huebner, and the ophthalmic and anterior temporal arteries.

To create the vessel wall, the computational vascular model was shelled with a thickness of 0.45mm, the minimum value possible with commercially-available 3D printing technology. The shelling develops the
A hollow characteristic of the computational core. In order to reduce costs of the model over its lifetime, the vascular tree was partitioned to allow for replaceable parts. Vasculature that did not have an aneurysm was left as a core, while aneurysmal portions remained as shells. A computer rendering of the aneurysmal shells is shown in Figure 1B. The partitioning method allows the aneurysmal portions to fit over the other, non-aneurysmal vascular portions like a “core-and-sleeve.” The computational process produced a water-tight surface mesh viable for 3D Printing.

[Figure 1]

Figure 1: A) Computational reconstruction and synthesis of nine patient datasets with aneurysmal lesions. B) Hollowed "sleeves" of aneurysms prior to 3D printing.

The vascular tree was 3D printed using an Objet500 Connex multi-material 3D printer (Stratasys, Eden Prairie, Minnesota, USA). The proposed vascular model was printed using an A27 Shore hardness photopolymer material. For educational purposes, the off-white, translucent vascular models were submerged in a red-dye coloring bath.

**Brain Model:**

The brain model was created using a multi-modality approach. A healthy patient MRI dataset was imported into Mimics and segmented. The resulting surface mesh was then imported into Geomagics where it was partitioned. The partitioning facilitated simulator operators in removing brain components in order to adjust or replace cerebral aneurysms without dismantling the entire simulacrum. The final computational surface mesh is shown in Figure 2A. The mesh consists of six separable components: 1) the left frontal and parietal lobes, 2) the right frontal and parietal lobes, 3) the left temporal and occipital lobes, 4) the right temporal and occipital lobes, 5) the cerebellum, and 6) the brainstem (with a truncated portion of the optic nerves).
A Stratasys Dimension 1200es 3D printer (Eden Prairie, Minnesota, USA) was used to print the final computational models in an acrylonitrile butadiene styrene (ABS) plastic. The surface underwent partial chemical dissolution with a 90:10 by volume solution of xylene and acetone in order to remove visible striations created during the 3D printing process.

A two-part mold was created around each solid component of the brain with a commercially-available casting silicone (Mold Star, Smooth-On, Easton, Pennsylvania, USA). These mold parts defined the negative shape of the intended brain. To cast the final brain components, a silicone with lower elastic modulus (Dragon Skin, Smooth-On, Easton, Pennsylvania, USA) was then mixed per manufacturer instructions with a pigment additive (Silc Pig, Smooth-On, Easton, Pennsylvania, USA). A tactile mutator (Slacker, Smooth-On, Easton, Pennsylvania, USA) was added, which further reduced elastic modulus. Following the cure time per manufacturer’s recommendation, the silicone brain was assembled.

Skull Model:
A CT dataset, from a patient featuring normal cranial morphology, was imported into Mimics and segmented. A latitudinal split was added to the skull to facilitate placement/removal of the brain and vascular models. The inferior portion of the cranium surface mesh model is shown in Figure 2B. The split allowed for easy adjustment of internal structures including the cerebral aneurysms and brain models. A zPrinter 650 (3Dsystems, Rock Hill, South Carolina, USA) was used to print the final model in a composite material. Tactile qualities of the composite material are similar to those of actual bone, especially with regards to medical equipment (such as a bone drill) according to pilot collaborating neurosurgeons. The final simulacrum consisted of the vascular tree and brain models assembled within the skull model.

[Figure 2]

Figure 2: Computational models prior to 3D printing for A) a patient-derived brain and B) a normal, patient-derived skull.
Qualitative Validation

To qualitatively validate the simulacrum, fourteen neurosurgical residents interacted with the simulacrum under the guidance of a neurosurgeon and provided qualitative feedback on its form and function. Evaluation covered the realism of the simulacrum when interacting with surgical tools (e.g., a bone drill) and medical devices (e.g., a vascular clips). A simple survey evaluating the simulacrum’s clinical applicability, realism, and educational value was completed by the medical professionals. The survey consisted of seven questions and ratings were provided on a five-point Likert scale.

Results

The authors built a simulacrum for simulating aneurysm clipping comprising of three distinct components (vasculature, brain, and skull). All three components were generated using 3D printing to recreate patient-derived geometries. The simulacrum featured a multi-hardness 3D printed photopolymer, an elastomeric cast, and a gypsum-composite material. The vascular tree and associated malformations were assembled in anatomically correct locations within the skull and brain using interchangeable parts. A completed simulacrum is shown in Figure 3.

![Figure 3](image-url)

Figure 3: A) 3D printed cranium featuring a craniotomy revealing an elastomeric brain. B) Forceps retract the left frontal and temporal lobes revealing a 3D printed middle cerebral artery aneurysm.

Fourteen neurosurgical residents, with an average post-graduate year of 3.3 (i.e., range 1-6 years) performed mock surgical interventions as shown in Figure 4. Orbitozygomatic and pterionalcraniotomies were first executed on the skull model. Aneurysm clips were applied to occlude the aneurysms included
in the vascular model. The average response for all survey questions was greater than 4 (range 4.1-4.6) on the five-point scale. Questions, mean responses, and ranges are shown in Table 1.

Table 1: Results of a Likert-survey to gauge efficacy of medical simulator. Neurosurgical residents (n=14) completed the post-assessment following interaction with the simulator. A score of 1 is strongly negative; 5 is strongly positive.

Discussion

There are three basic approaches to simulation development: 1) cadaveric tissue models (human or animal), 2) computer-based or virtual reality systems, and 3) synthetic physical models. Each of these approaches has been employed in neurosurgical simulation before, and each has advantages and disadvantages. For aneurysm clipping needs, the authors identified the proposed model as having the greatest potential to provide a low cost and effective means of training residents in the following skills: 1) appreciating the views and depths of field of common cerebral aneurysms after standard craniotomies, 2) recognizing realistic aneurysm shape, and 3) identifying the relationships between common aneurysms and their parent arteries, as well as neighboring vessels.
Strengths

The proposed simulacrum has a number of strengths as an effective surgical simulator with regards to anatomical awareness, basic principles of tissue handling, and development of surgical skill.

First, the simulacrum integrated the brain and cranium, which are essential in training of the early stage surgeon to locate and visualize cerebral aneurysms. In addition, the proposed simulacrum – including brain, cranium, and vascular tree – provides a patient-derived representation of the working space and field-of-view in craniotomy-based aneurysm surgery. The skull, vasculature, and brain used in the simulator are of accurate anatomic scale. This geometric accuracy helps the trainee to perform a standard craniotomy under realistic conditions and gain an appreciation of what may be observed during a surgical intervention. While current 3D printing technology could not replicate vessels smaller than 1mm in diameter, the truncated vascular tree was deemed to benefit learners early into their program development by supervising neurosurgeons. Further developments in 3D printing technology may raise the fidelity of the model to have greater impact on anatomical understanding with more expert level learners such as already-practicing surgeons.

Second, the simulacrum includes multiple hollow cerebral aneurysms allowing for a single simulator to be used in understanding many of the aneurysms typically encountered in clinical practice. Early efforts to generate cerebrovascular simulacra include D’Urso et al. where modeling of the cerebral arteries employed 3D printing technology. These early models were primarily limited to rigid, non-hollow materials. The hollow quality of the proposed simulacrum enables realistic delivery of a standard permanent aneurysm clip to the aneurysm and permits a clip to be applied that collapses the aneurysmal dome. The tactile experience of placing a clip across the neck of an aneurysm and witnessing a change in the vessel morphology was commented as a positive experience by learners in the test group. A larger educational study would be needed to confirm the learners’ experiences
translate to better acquired microsurgical dexterity. Precedent work by Wurm et al. and Seong et al. used 3D printing to develop hollow aneurysm models for educational purposes\textsuperscript{15,25}. While these efforts permitted multiple, hollow aneurysms to be represented, the simulators lacked one or more of the proposed simulacrum’s other features (e.g., the brain and cranium). The proposed simulacrum demonstrated utility in conveying the 3D morphology of an aneurysm and its relationships to neighboring neurovasculature. The brain and skull provided surgical landmarks for the user as well as realistic limitation to the surgeon’s field of view according to collaborating neurosurgeons.

Third, the vascular model is modular. While the entire simulacrum costs under $1,000 for initial manufacturing, the modular constructions permits lower cost (less than $10 material cost) replacement of parts that are worn out, and allows for insertion of a specific aneurysm to suit specific teaching goals. Aneurysms can be removed and exchanged without replacing the entire system. An additional advantage of the modular system is that a patient specific aneurysm can easily be printed and then integrated directly into the system. Wurm et al. and Seong et al. have also developed modular components\textsuperscript{15,25}. The adaptive qualities of the simulator facilitate educational deployment and may have potential to enable surgical planning prior to an actual operation. Future 3D printing technologies, with greater accuracy and faster printing times, will enable the use of simulacra for high-fidelity, patient-specific surgical planning simulations.

Following the qualitative validation, the medical professionals rated the geometric representation and tactile experience as realistic in the context of medical simulation. In particular, the professionals felt that the tactile response from the vasculature and brain could improve cognitive and psychomotor control development, especially after repeated simulations. All participants considered the simulacrum to have valuable potential in a medical classroom. While this analysis is far from quantitative, it does demonstrate potential of simulacrum efficacy.
Limitations

In its current form, the simulacrum has three noteworthy limitations. First, an important consideration in aneurysm surgery is the relationship between the vasculature and the cranial nerves. Currently, the model only integrates a truncated portion of the optic nerve. Other cranial nerves were not included. Plans for the second generation of the simulacrum include the integration of other cranial nerves using the same silicone casting method as was used for the optic nerve and brain in the current design iteration. In addition, the 3D printing technology could only capture major vasculature structures. Small vessels and perforators are not possible with current technology. To validate the accuracy of the vessels that were printed, the volume of the computational model was compared to the volume of material printed; there was no discernable difference between the two models. Despite the 3D printing limitations, the vessels that were printed maintained high accuracy to reconstructed models.

Second, the current simulacrum does not allow for an arachnoid dissection to be performed. Emerging rapid prototyping technologies will likely allow for inclusion of the meningeal layer as material properties continue to allow thinner material deposition with varying material properties. Nevertheless, the authors are focusing efforts (using other modalities) to develop a simulacrum that can be created with current 3D printing technology that allows for simulated arachnoid dissection.

A major limitation of the proposed vascular model is the over-accentuated wall-thickness in the hollow vessel portions, which is a problem that others in the field have also worked to solve. Kimura et al. developed a hollow aneurysm model made with a soft elastic silicon material that could receive a clip. Mashiko et al. later developed a method whereby they printed vasculature using a rigid material and subsequently casted the material with silicone to create a hollow model (in a manner similar to the fabrication of the proposed simulacrum’s brain model). While the latter method leads to a less regulated wall thickness, it can create thinner walls and also requires less time than both the authors’
method and the curettage method used by Kimura et al. However, recent advances in 3D printing technology may lead to immediate improvements to the authors’ design.

In addition to simulacrum limitations, the educational study was limited in scope. Additional studies with this simulacrum and others will be needed to elucidate critical educational information such as how often should a simulation be performed on simulacra in order to maximize a learner’s response. Furthermore, interactions with operations of different skill levels, resident and beyond, need to be further studied to determine simulation efficacy on different expert levels. The results and findings of the education study presented here should be taken as preliminary data to support a larger and more comprehensive educational study with high-fidelity medical simulations.

Conclusions

The demands of cerebrovascular surgery create a need to supplement conventional patient care-based education of medical professionals. Educational tools based on simulation have demonstrated promising utility in meeting that need. The authors have developed an aneurysm clipping simulacrum that supplements the training of neurosurgical residents who are learning to perform aneurysm surgery. The simulacrum represents potential as a valuable tool for neurosurgical education, medical assessment, and even surgical planning. Simulations offer the unique capability to create realistic medical scenarios without the inherent risks of patient care. Future work will include enhancing the simulacrum to include all of the cranial nerves, developing techniques to allow for flow within the vascular model, and validating the overall simulator as a tool for cultivating neurosurgical skill.
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Declaration of Conflicting Interests

The authors have no potential conflicts of interest relevant to this article.

References


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<thead>
<tr>
<th>Question</th>
<th>Average Response (Range 1-5)</th>
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<tbody>
<tr>
<td>1. Is the simulator clinically applicable?</td>
<td>4.4 (4-5)</td>
</tr>
<tr>
<td>2. Did the simulator improve your understanding of the aneurysm's relation</td>
<td>4.4 (3-5)</td>
</tr>
<tr>
<td>3. Did it improve your understanding of the surgical view?</td>
<td>4.5 (4-5)</td>
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<tr>
<td>4. Did clip application seem realistic?</td>
<td>4.1 (3-5)</td>
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<tr>
<td>5. Did the bone drill in a realistic manner?</td>
<td>4.1 (2-5)</td>
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<tr>
<td>6. Was the simulator useful to you?</td>
<td>4.6 (4-5)</td>
</tr>
<tr>
<td>7. Do you think your surgical skills would improve with practice using</td>
<td>4.4 (4-5)</td>
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<td>the simulator?</td>
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Highlights

• A multi-material, 3D printed, patient derived aneurysm clipping simulator is proposed.

• The simulator features a synthesis of multiple patient lesions.

• The simulator features a modular systems to facilitate delivery of new aneurysmal morphology and replacement of damaged anatomy analogues.

• The simulator is placed though an educational pilot study.
The authors have no conflicts of interest to disclose.