Simulation-Based Education for Ventriculostomy: 
A Study for Medical Students

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ABSTRACT
Medical students and surgical residents develop medical and surgical knowledge through various media including lectures, textbooks, publications, and other content delivery mechanisms. These learning mechanisms are vital to educational success; however, textbook knowledge does not necessarily translate to acquisition and mastery of procedural skills. Development of surgical skills toward mastery requires direct intervention on a patient, specialized educational environments (e.g., a cadaver lab) for and/or a patient simulator. The purpose of a simulator is to develop procedural knowledge. Procedural knowledge involves two main functions as defined by Kahol et al., which are cognitive and psychomotor functions. An effective medical simulation enhances the learning of both behavioral functions. Simulacra, the physical, non-curricular components of simulators, replicate anatomies consistent with learned content knowledge, while the simulator’s curricula target the learner’s development of procedural skills. Learners are often compelled to reconcile content knowledge with procedural knowledge. Through the use of a simulator, learners progress toward mastery of surgical skills outside of the risk-inherent environment of an operating room. The learner is free to focus on the development of cognitive and psychomotor skills without the risk of catastrophic consequences. Simulation in this context is a method of cognitive training that has been thoroughly validated.

Keywords: Simulation-based education, ventriculostomy surgical simulation, medical students

INTRODUCTION
Educators can leverage the strengths of medical simulators to effectively teach complex and high-risk surgical procedures, such as placement of an external ventricular drain (EVD). This procedure is used to monitor intracranial pressure (e.g., in trauma patients or patients presenting with a Glasgow coma scale of 3-8 or less [64]) or to treat symptoms of hydrocephalus (such as patients with decreased cerebrospinal fluid (CSF) absorption due to subarachnoid hemorrhage or ventriculitis or patients with CSF pathway obstruction due to tumors, cerebral hemorrhages, etc.)[65]. CSF release is recommended in patients with SAH grade II or higher according to American Heart Association/American Stroke Association [66]. These sources of increased ventricular pressure, and the subsequent need for that pressure to be alleviated, presents a need for surgeon mastery of the ventriculostomy procedure. In fact, placement of an EVD constitutes one of the first bedside procedures learned in residency training and one of the most common procedures performed in the neurosurgical field [67], [68]. To improve neurosurgery education capabilities, the authors developed a ventriculostomy simulator leveraging the latest in rapid prototyping technologies in conjunction with traditional casting techniques (both elastomer and hydrogel). Virtual or mixed simulators for ventriculostomies have been developed previously [67], [70]; however, the prior computer-based simulators had high associated costs in terms of both equipment and facilitators. We describe the development of a cost-effective physical simulator for ventriculostomy placement. The goal of the proposed simulacrum is to facilitate medical simulation by teaching three cognitive tasks: 1) develop an understanding of the geometry associated to the cranium and its landmarks in relation to the frontal horn of the lateral ventricles, 2) develop an awareness of the common ventriculostomy field of view, and 3) gain familiarity with the instruments and the methods used in deploying a ventricular cannula. The simulacrum features the integration of patient-derived cranium, brain, and lateral ventricular spaces. A simplified gravity-driven pump generates a constant ventricular pressure based on facilitator demands. The material choices for each component provide appropriate turgor and recoil to adequately simulate the surgical experience according to a limited qualitative study. The educational study also serves to establish potential efficacy of the model according to a technology acceptance model (TAM) [25]. The model is an attempt to quantify perceived usefulness and perceived ease-of-use of a
new technology. Without the perception of efficacy, the simulator would fail to be adopted into standard educational practice. The techniques for developing the model, the educational study, and the associate advantages and disadvantages are discussed.

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The goal of the proposed simulacrum is to facilitate medical simulation by teaching three cognitive tasks: 1) develop an understanding of the geometry associated to the cranium and its landmarks in relation to the frontal horn of the lateral ventricles, 2) develop an awareness of the common ventriculostomy field of view, and 3) gain familiarity with the instruments and the methods used in deploying a ventricular cannula. The simulacrum features the integration of patient-derived cranium, brain, and lateral ventricular spaces. A simplified gravity-driven pump generates a constant ventricular pressure based on facilitator demands. The material choices for each component provide appropriate turgor and recoil to adequately simulate the surgical experience according to a limited qualitative study. The educational study also serves to establish potential efficacy of the model according to a technology acceptance model (TAM)[25]. The model is an attempt to quantify perceived usefulness and perceived ease-of-use of a new technology. Without the perception of efficacy, the simulator would fail to be adopted into standard educational practice. The techniques for developing the model, the educational study, and the associate advantages and disadvantages are discussed.

METHODS – Computational Modeling

The initial computational model for the simulacrum was derived from two datasets. Head MRI data were acquired with 1.5mm slice thickness and 0.488mm pixel spacing in images of 512x512 pixels. Skull CT data were acquired with 0.625mm slice thickness and 0.488mm pixel spacing in images of 512x512 pixels. The resulting images were packaged into two Digital Imaging and Communication in Medicine (DICOM) files and imported into Mimics (Materialise, Lueven, Belgium), a medical image processing software suite.

The software facilitated image segmentation, the process of separating regions of an image into discrete subsets. Three subsets resulted from segmentation: brain, skull, and lateral ventricles. These masks were reconstructed into three-dimensional (3D) surface mesh models. Skull and cerebral models were then imported into an engineering software suite.

The inferior third of the skull was removed to reduce simulator costs, and the posterior aspect of the skull was removed to create an opening for the installation and removal of the brain model. Two windows were cut from the superior aspect of the skull to allow the interchanging of disposable bone plates for burr-hole placements, allowing multiple attempts during simulation. The brain model was truncated at the same position as the skull model. Undercuts created by deep sulci were removed to prevent issues with molding and casting. The lateral ventricles were also truncated, and a back plate was added to the ventricular system to facilitate molding and casting. The computational models of the brain with ventricles and truncated skull are shown in Figure 2.
METHODS – Physical Modeling

The adjusted skull model was printed using a zPrinter 650 with 0.1 mm layer thickness. This additive manufacturing process prints a cyanoacrylate binding agent onto a gypsum-powder medium, creating a final material similar to bonded plaster. Tactile qualities of the composite material are similar to those of actual bone, especially when handled with surgical instruments (e.g., a manual twist drill). Additional bone windows as described in the preceding section were also printed as shown in Figure 2a. A Stratasys Dimension 1200es was used to print the final brain and ventricle models in an acrylonitrile butadiene styrene (ABS) plastic medium with a layer thickness of 0.254mm. This additive process heats a plastic spindle and extrudes it onto a platform, depositing material as a single layer. The process is repeated layer-by-layer until the model is complete. Support material is removed in a heated, caustic (sodium hydroxide) bath. For the brain and ventricle prints, the plastic surface underwent selective chemical dissolution with a 90:10 by volume solution of xylene and acetone, respectively. The models were submerged in a secondary bath of isopropyl alcohol (91% by volume) to preserve optimal surface quality. Optimal quality is defined as removal of all visible striations inherent to additive manufacturing processes.

A silicone spray release agent was used to coat the plastic brain model. The plastic brain component was then placed inside a mold box and covered with a temperature resistant casting silicone. This process was repeated with the ventricles. Once cured, plastic components were removed from the silicone molds. A silicone cast was then created in the ventricular mold to generate the two elastomeric ventricular cores as seen in Figure 3b.

A mixture of gelatin and agar gel powder (90:10 by weight) was added to distilled water (at 75°C) to achieve the desired gel concentration (1.2% by weight). The solution was stirred until homogenous and allowed to cool to room temperature. The gel was then placed in a 65°C water bath for an hour and returned to room temperature before another round of heating ensured hydration of the hydrogel powder.

The brain mold and ventricle casts were coated with common cooking oil as a release agent. The heated gelatin/agar solution was poured into the brain silicone mold. The ventricle cores were inserted into molten medium, and the gel was cooled to room temperature. The brain was extracted from the mold prior to ventricular core removal. The brain model, shown in Figure 3d was placed into the skull model to complete the proposed ventricular simulacrum as shown in in Figure 3a.
METHODS – Educational and Technology Acceptance Study

The assembled model was trialed by a group of medical students and residents (n=10) to qualitatively determine the simulator’s efficacy and establish the foundation for a future multi-cohort educational study. A 4th year post-graduate neurosurgery resident served as the facilitator for this study. A short curriculum based on standard practices used to complete a ventriculostomy was presented to the students. The ventriculostomy procedure started with drilling of a burr hole at Kocher’s point, approximately 10 cm posterior to the glabella, a landmark included on the simulator, and 2.5 cm lateral to the midline. Manual twist drill was used to create the burr hole, and the blunt end of the tunneling trocar was used to clear away any bone-analogue chips from the burr hole. A standard ventricular catheter was advanced into the burr hole and brain at an appropriate angle using anatomical landmarks as guides. The ventricular catheter was advanced approximately 6.5-7 cm to the edge of the bone. Placement success was determined by the presence of CSF analog fluid flowing from the ventricular catheter after stylet removal. An observer recorded the number of passes through the brain needed to obtain CSF flow.

Prior to surgical simulation and curricula deployment, students completed a pre-assessment questionnaire evaluating student familiarity with the ventriculostomy procedure. Following simulation, students completed a post-assessment survey with the same questions as the pre-assessment questionnaire. The latter survey included an additional 20 questions based on an expanded TAM model by Davis et al. and Dabholkar and Bagozzi[25], [26]. Domains in this modified TAM include awareness/presence, attitude, perceived usefulness, perceived ease-of-use, enjoyment, and intention-to-use. The standard five-point Likert-scale was used to qualify responses (1 being strongly negative in response, 5 being strongly positive)

RESULTS

The simulator was used by 10 individuals with varying degrees of expert level. Medical students (n=4) and residents (n=6) from 0-5 post-graduate years (PGY) utilized the simulator. Five out of the six residents completed the simulation on the first attempt; all medical students and one 2-PGY resident needed multiple attempts to place the catheter into the ventricle. A comprehensive breakdown of all questions and responses related to the technology acceptance component of the survey is included in Table 16. All responses in response gauged the perceived educational efficacy (as defined by the domains in the TAM) with means greater than “neutral” (3 on the deployed Likert-scale).
Table 1 (next page): TAM post-assessment responses.

<table>
<thead>
<tr>
<th>Technology Acceptance Questions (n=10)</th>
<th>Score</th>
<th>mean ± std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Awareness/Presence</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The tactile response of the bone helps me understand how far to drill.</td>
<td>3.7</td>
<td>± 1.0</td>
</tr>
<tr>
<td>The tactile response of the brain media helps me understand if the catheter is in the ventricle</td>
<td>3.8</td>
<td>± 0.9</td>
</tr>
<tr>
<td>The cranial field of view helps me practice for a realistic intervention.</td>
<td>4.0</td>
<td>± 0.8</td>
</tr>
<tr>
<td>The patient derived model helps me appreciate anatomical landmarks.</td>
<td>3.9</td>
<td>± 0.8</td>
</tr>
<tr>
<td><strong>Perceived Usefulness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The simulator improved my performance of a ventriculostomy.</td>
<td>4.1</td>
<td>± 0.7</td>
</tr>
<tr>
<td>The simulator improved my understanding of the relationship of the ventricles to the cranium.</td>
<td>4.0</td>
<td>± 0.8</td>
</tr>
<tr>
<td>The simulator has increased my confidence in performing a ventriculostomy in a patient.</td>
<td>4.0</td>
<td>± 0.8</td>
</tr>
<tr>
<td>What I have learned in the simulator will impacted patient care.</td>
<td>4.0</td>
<td>± 0.8</td>
</tr>
<tr>
<td>The simulator was an effective use of my time.</td>
<td>4.2</td>
<td>± 0.8</td>
</tr>
<tr>
<td><strong>Perceived Ease-of-Use</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The simulator was not cumbersome or difficult to interact with</td>
<td>4.1</td>
<td>± 0.9</td>
</tr>
<tr>
<td>This low cost simulator was well-designed.</td>
<td>4.3</td>
<td>± 0.7</td>
</tr>
<tr>
<td>The simulation did not take an unnecessary amount of time to complete.</td>
<td>4.4</td>
<td>± 0.9</td>
</tr>
<tr>
<td>The simulator was effective with some instruction.</td>
<td>4.7</td>
<td>± 0.5</td>
</tr>
<tr>
<td>The simulator would be effective without any instruction.</td>
<td>3.7</td>
<td>± 0.9</td>
</tr>
<tr>
<td><strong>Enjoyment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I enjoyed this simulator as an educational tool.</td>
<td>4.3</td>
<td>± 0.8</td>
</tr>
<tr>
<td>I enjoyed this simulator regardless of the potential educational value.</td>
<td>4.1</td>
<td>± 1.1</td>
</tr>
<tr>
<td><strong>Attitude</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The simulator will improve my surgical skills if given time to practice.</td>
<td>4.3</td>
<td>± 1.0</td>
</tr>
<tr>
<td>I have a positive attitude about this simulator.</td>
<td>4.6</td>
<td>± 0.6</td>
</tr>
<tr>
<td><strong>Intention-to-Use</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The simulator encourages me to practice this medical intervention.</td>
<td>4.1</td>
<td>± 1.0</td>
</tr>
<tr>
<td>I wish simulators like this were created for other common procedures.</td>
<td>4.4</td>
<td>± 0.7</td>
</tr>
<tr>
<td>I would recommend this simulator for other learners.</td>
<td>4.4</td>
<td>± 0.7</td>
</tr>
</tbody>
</table>
There are three basic approaches to medical 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, and each has its own advantages and disadvantages. For example, cadaveric dissection is well-accepted and introduces students and residents to surgical anatomy and psychomotor skills. The cost of cadavers and the necessary facilities to preserve, accommodate, and maintain the specimens, however, is increasingly cost-prohibitive [72]. In addition, cadaveric models can lack the anatomical accuracy reflected in living patients. For example, a cadaver will not be able to illustrate the real-time scenario of increased ventricular pressure. One method to circumvent these limiting factors of cost, availability, and ability to simulate real-time pathology is to construct medical simulators. We believe the proposed model has great potential to provide a low-cost and effective method of training residents in the following skills: 1) understanding of cranial geometry and its and marks in relation to the frontal horn of the lateral ventricles, 2) recognition of the appropriate entry point for ventriculostomy catheter placement, and 3) acquisition of familiarity with the instruments (e.g., manual twist drill, catheters, trocar, etc.) and the methods used in deploying a ventricular catheter. However, inherent to any simulator (physical or virtual) are simplifications of anatomy and physiology.

The proposed simulacrum utilizes advanced rapid prototyping technologies and casting techniques to produce an effective surgical simulator. The simulacrum includes structures that simulate a realistic surgical field. The brain, lateral ventricular system, and skull are all of accurate anatomical scale, given that they are derived from patient data. Ventricular anatomy can be easily manipulated to represent abnormal anatomy if desired (e.g., displacement by a hemorrhage or tumor), since the mold pieces are separated in the casting process (brain parenchyma from ventricles); this compartmentalization in design imparts modular capability to the simulator. Ventricular geometries can be extracted from different patient datasets, reconstructed as 3D geometries, and then printed in a format compatible with the casting methods. A facilitator could have multiple malformed ventricular geometries, simulating a progression of disease or differences among diseased morphologies.

Rapid prototyping has been broadly applied in the medical community [24], [73]. Early applications in generating cerebroventricular simulacra include Bova et al. where the modeling of the cranium employed additive manufacturing technology, but the ventricular systems was represented using a computer-generated haptic-feedback system [74]. These early models, while achieving a high level of anatomical complexity, were costly given they are “mixed-simulators” that contain elements of physical modeling as well as virtual, haptic systems. The systems developed by Bova et al. included an electromagnetic tracking system. Our model achieves anatomical accuracy through 3D printing while maintaining low costs with readily available materials. Once initial molds have been created, final brain casts are produced using common and accessible materials. As of the publication date, material costs were approximately $4 per brain model.

Regardless of cost, a simulator can only be considered effective if it facilitates development of cognitive and psychomotor skills. The proposed simulacrum demonstrated utility in conveying the location of the ventricle with respect to anatomical landmarks on the cranium, as evidenced by the pilot educational study. For example, following the insertion of the catheter, the learner is charged with locating the ventricle. 80% of the neurosurgery residents completed a successful ventriculostomy on the first attempt, while all medical students needed multiple attempts to succeed in catheter placement. This result suggests that increased surgical experience (it is assumed a resident has more years of experience than a medical student) results in a stronger performance on the simulator. Conversely, this result suggests that there is a gap to be filled in training medical students to effectively locate ventricles early on in their careers.

Following the simulation study, analysis of the TAM responses revealed positive trends in the perceived efficacy of the simulator. All TAM responses had a mean greater than 3, suggesting
that the model is better than the status quo in ventriculostomy education. All questions coded as perceived usefulness, attitude, and intent-to-use had means equal to or greater than 4.0 (positive) with standard deviations at or below 1.0. The positive trends in the TAM responses are evidence of the simulacrum’s efficacy.

There are several limitations to the current simulator model. First, the material properties of the brain analogue are not philologically accurate. The human brain is not a homogenous medium with anisotropic material properties. The medium that we have developed are similar to other hydrogel models [63], [76]–[78] that use a homogenous mixture to achieve a constant tactile response. This moderate sacrifice in realism was made to reduce material costs.

Secondly, the simulacrum simulates neither dura nor arachnoid mater. These meningeal layers encapsulate the sub-arachnoid space, which may also exhibit increased CSF pressure in the presence of trauma or disease. Current 3D printing processes make this component of the simulacrum both challenging and impractical to model. Nevertheless, the authors are investigating other casting methods to develop a cost-effective process for simulating arachnoid dissection in future iterations of the simulacrum. Multi-material 3D printing may be another method of simulating the complex stratification and presentation of multiple tissues. Specifically, Digital Material printing (Stratasys, Rehovot, Israel) utilizes a series of photopolymers with a spectrum of Shore hardnesses and other material properties. Future computational modeling schemes may leverage volumetric modeling as opposed to surface mesh modeling to facilitate this multi-material printing. Current mechanisms for multi-material printing require discrete regions describing material properties. A volumetric modeling approach, where voxels can be assigned material properties, may result in a print with a gradient of material properties. For simulacra where cost considerations are less critical, this 3D printing modality may enable the construction of a higher fidelity simulacra.

Another limitation is geometric idealization (to facilitate cost-effective casting process). When reconstructing the brain matter, the inner surfaces of sulci were removed. The final representation includes gyri and impressions of the sulci for the purposes of surface landmarks. While virtual, haptic systems may be able to capture this form of undercut geometry, collaborating neurosurgeons considered these components less important than the cost-effective nature of the simulacrum. The current model only contains the superior lateral horns of the ventricles. Recent advances in elastomeric printing may make these geometric sacrifices unnecessary; however, it will be up to institutions to balance cost with geometric and tactile accuracy.

A limitation to the TAM used to validate the potential efficacy of the simulacra relates to the study size. Only 10 individuals trialed the simulator and provided feedback. The intent of the study was to provide early qualitative support for the simulator, which was favorable. To better gauge the efficacy of the simulator, a multi-cohort, randomized trial should be performed.

Conclusion

EVD placement is one of the most common (yet challenging), life-saving procedures performed by a neurosurgeon, and also one of the first learned in residency training. Since cadaveric models do not reflect “live” or “real-time” anatomical functions of the ventricular system, simulators are a promising route for medical students and interns to learn this high-risk procedure. Haptic-based systems, while effective, have high associated costs. We have developed a low-cost simulacrum to train medical students and neurosurgical residents in ventriculostomy placement. While 3D printing techniques have enabled anatomical representation, such as the PHDMs, 3D printing can also address more complex educational systems. Advanced 3D printing and casting techniques enabled the creation of a cost-effective simulator with advantageous realism in comparison to state-of-the-art virtual and/or mixed alternatives. An initial qualitative study suggests that the simulacrum may be valuable for neurosurgical education. Future models will aim to enhance anatomical and physiological accuracy by adding the complete ventricular system, as well as additional cranial and brain tissues (e.g., scalp and meninges).

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