Low-cost endoscopic third ventriculostomy simulator with mimetic endoscope

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OBJECTIVE Hydrocephalus affects approximately 1 in 500 people in the US, yet ventricular shunting, the gold standard of treatment, has a nearly 85% failure rate. Endoscopic third ventriculostomy (ETV) is an alternative surgical approach for a specific subset of hydrocephalic patients, but can be limited by the inability of neurosurgical residents to practice prior to patient contact. The goal of this study was to create an affordable ETV model and endoscope for resident training.

METHODS Open-source software was used to isolate the skull and brain from the CT and MR images of a 2-year-old boy with hydrocephalus. A 3D printer created the skull and a 3D mold of the brain. A mixture of silicone and silicone tactile mutator was used to cast the brain mold prior to subsequent compression and shearing modulus testing. A mimetic endoscope was then created from basic supplies and a 3D printed frame. A small cohort of neurosurgical residents and attending physicians evaluated the ETV simulator with mimetic endoscope.

RESULTS The authors successfully created a mimetic endoscope and ETV simulator. After compression and shearing modulus testing, a silicone/Slacker ratio between 10:6 and 10:7 was found to be similar to that of human brain parenchyma. Eighty-seven percent of participants strongly agreed that the simulator was useful for resident training, and 93% strongly agreed that the simulator helped them understand how to orient themselves with the endoscope.

CONCLUSIONS The authors created an affordable (US\$123, excluding 3D printer), easy-to-use ETV simulator with endoscope. Previous models have required expensive software and costly operative endoscopes that may not be available to most residents. Instead, this attempt takes advantage of open-source software for the manipulation and fabrication of a patient-specific mold. This model can assist with resident development, allowing them to safely practice use of the endoscope in ETV.

<https://thejns.org/doi/abs/10.3171/2018.2.PEDS17671>

KEYWORDS ETV simulator; silicone; mimetic endoscope; 3D printing; neurosurgical resident training; hydrocephalus; surgical technique

HYDROCEPHALUS, a condition caused by excess production or decreased absorption of CSF, affects approximately 1 in 500 people in the US.¹⁹ This imbalance of CSF absorption/production can lead to increased ventricular size and compression of vital brain structures.¹³ Ventricular shunting, the gold standard of treatment, has a nearly 85% failure rate.⁹ Endoscopic third

ventriculostomy (ETV) is an alternative surgical approach to ventricular shunting but is limited to a specific subset of hydrocephalic patients whose hydrocephalus is due to aqueductal stenosis secondary to congenital aqueductal stenosis, aqueductal webs, infection, or tumor compression of the aqueduct of Sylvius or fourth ventricle outflow.¹¹ Although ETV is a common and well-tolerated

ABBREVIATIONS ABS = acrylonitrile butadiene styrene; ETV = endoscopic third ventriculostomy; MPRAGE = magnetization-prepared rapid acquisition gradient echo; NIFTI = Neuroimaging Informatics Technology Initiative; PLA = polylactic acid; STL = stereolithography.

SUBMITTED December 3, 2017. **ACCEPTED** February 19, 2018.

INCLUDE WHEN CITING Published online May 11, 2018; DOI: 10.3171/2018.2.PEDS17671.

procedure, there are significant risks and complications that can occur.^{8,18} To reduce risk and complications, the surgeon must have adequate exposure to the technique. In the case of ETV, this training is often limited by a steep learning curve and little access to costly training simulators prior to direct patient contact. Disorientation with the endoscope and loss of anatomical landmarks can occur, leading to injury to the fornix, mammillary bodies, or basilar artery, resulting in irreversible memory loss or catastrophic hemorrhage.^{1,12} Training on large animal models or human cadavers is a viable option but proves to be cost-prohibitive and nonreproducible. Furthermore, large animal models do not always provide the same anatomical landmarks, and human cadavers lack the tactile feedback one would encounter in a live patient.

In contrast, artificial surgical ETV simulators are potential solutions that provide a risk-free environment to aid in the development of the necessary neurosurgical skill set needed to perform an ETV safely. Besides virtual reality-based models, previous hands-on ETV simulators have included those fabricated using resin, silicone, and synthetic rubber.^{2,5,6} Despite these efforts, none of these models have accounted for the modulus of elasticity when preparing the brain phantom, and all models have relied on costly operating room-grade endoscopes with a light source tower. The goal of this study was to create a low-cost ETV model with an endoscope for resident training.

Methods

This study was performed in compliance with the Wayne State University IRB. The model consists of a skull model, silicone brain phantom, anatomical intraventricular mimetics, and a mimetic endoscope. To create this framework, open-source software was used to isolate the skull and brain from the CT and MR images of a 2-year-old boy with obstructive hydrocephalus. A skull model and brain mold were then 3D printed, with the skull used unmanipulated and the brain mold used to cast a silicone brain phantom. The silicone brain phantom was placed in the 3D printed skull model to mimic human anatomy. The anatomical intraventricular mimetics (choroid plexus, thalmostriate vein, septal vein, third ventricle floor, basilar artery) were placed, and the ETV model was submerged in water to recreate a closed system. A mimetic endoscope was then created and used to perform the ETV procedure.

Skull Model Preprocessing

To model the skull, DICOM images of a noncontrast CT head scan with 1-mm slices were loaded into the free version of OsiriX (Pixmeo).¹⁶ The threshold tool was used to isolate the skull from bone window sequences to take advantage of heightened density/threshold compared with surrounding tissue. Once isolated, a 3D surface was rendered and exported as a stereolithography (STL) file (Fig. 1). Next, the free open-source software MeshLab was used to ensure the STL file was manifold, or without internal defects that would cause the mesh to misprint.⁴

Brain Mold and Phantom Preprocessing

The brain mold and phantom both were created from

a preprocessed STL file following file conversion in the free open-source software MRICron and manipulation in the free open-source software program Freesurfer (<http://surfer.nmr.mgh.harvard.edu/>). DICOM-formatted, 1-mm sliced, T1-weighted MRI brain magnetization-prepared rapid acquisition gradient echo (MPRAGE) images were opened in MRICron using the “dcm2nii” (DICOM to Neuroimaging Informatics Technology Initiative [NIFTI]) tool and converted to NIFTI file format.¹⁵ Next, Freesurfer was used to extract the brain parenchyma from the MRI.¹⁴ At this stage, Freesurfer replaced OsiriX, as OsiriX could not be used for isolation of the brain from the MRI as was done with the skull modeling. This was secondary to the similar intensity thresholds shared among brain parenchyma, dura, and scalp tissue. Extraction of the brain parenchyma from the MRI is accomplished by entering the “recon-all” command in the desktop command terminal once Freesurfer has been opened and installed.¹⁴ The recon-all command is an all-inclusive complex set of computer algorithms that will result in stripping of the scalp, skull, and other structures, leaving the left and right cerebral hemispheres only (Fig. 1).¹⁴ Next, still in Freesurfer, the pons, medulla, and cerebellum were isolated. The file was subsequently converted to NIFTI format using the “mri_convert” command. Using the “mri_binarize” command, the subcortical structures that were not of interest were removed (see <http://surfer.nmr.mgh.harvard.edu/> for a complete list of specific subcortical structures).¹⁴ The command “fslmaths” was next used to create an NIFTI file containing only the subcortical regions of interest (pons, medulla, cerebellum). Lastly, the command “mri_tessellate” was used to create the final 3D model of the pons, medulla, and cerebellum. The command “mris_convert” was then used to create an STL file. Total time using a desktop computer (Apple Mac mini, late 2014, 2.6 GHz Intel Core i5, 8 GB RAM) was 12 hours.

Skull and Brain Mold Fabrication

Once the skull and brain mold files were converted to STL file format, the free open-source software Meshmixer, with inspector tool and auto-repair function, was used to repair imperfections that prevented the skull or brain phantom STL files/meshes from being manifold.¹⁷ The skull and brain mesh surfaces appear rough and are improved by using the Laplacian smooth function in MeshLab (Fig. 1). It should be noted that if the brain mesh is not adequately smoothed, extraction of the brain phantom will be more difficult.

The free open-source software program Blender (<https://www.blender.org/about/license/>) was used to overlay a simple solid cube and the brain mold mesh. Subsequently, the Boolean operator function was performed between the cube and the brain phantom mesh to create the brain mold (a negative mold of the brain in the cube). The x-ray feature, for enhanced visualization, was used to confirm successful processing. The model was reopened in MeshLab as an STL file for confirmation of a manifold mesh. Meshmixer’s “plane cut” tool was used to visualize and divide the mold into 4 equal pieces with a horizontal and vertical plane cut. Files were saved as STL files immediately prior to print.

FIG. 1. Three-dimensional rendering and preparation of skull and brain parenchyma. Freesurfer software with oblique (A) view of brain after processing. Skull (B) opened in MeshLab for postprocessing after creation of 3D surface in OsiriX. Cura software was used for preparation of the skull with (C) and without (D) support structures and the creation of gcode for 3D printing. Three-dimensional printing of skull with support structures (E). Figure is available in color online only.

Three-Dimensional Printing Skull Model and Brain Mold

A Lulzbot Taz 6 3D printer (Lulzbot, Aleph Objects Inc.) was used for all 3D printing. This printer was chosen for its cost efficiency, heated print bed, large maximal print volume, auto-cleaning feature, and auto-leveling abilities. Other printers we considered required manual leveling for each print or were cost-prohibitive. The free open-source software Cura was used to convert STL files to gcode, a process to amend files with coordinates recognizable by most 3D printers. Cura also allowed for rescaling, adjusting fill density, refining printer settings for different print materials, and creation of support structures to ensure a successful print. Polylactic acid (PLA) filament (eSUN) was used to print the skull model (Fig. 1) and acrylonitrile butadiene styrene (ABS) filament (Mitus) to print the brain mold (Fig. 2).

Silicone Brain Phantom Fabrication

The two left-sided pieces of 3D printed brain mold were placed together and the sides sealed with silk tape. The same procedure was performed for the two right-sided pieces. Prior to filling the molds, a release agent (Ease Release 200, Smooth-On) was sprayed over the surface. A 10:6 silicone/Slacker (a silicone tactile mutator; Smooth-On) ratio was used to fill the molds and allowed to cure overnight (Fig. 2). The silicone-filled mold halves were then immersed in distilled water where the mold was removed, leaving the intact brain phantom. The brain phantom was then removed from the distilled water and placed in the previously printed skull model (Fig. 3). A small hole was created with scissors where Kocher's point would overlie to communicate with the right lateral ventricle. The plunger was removed from a 10-ml syringe

and the distal end cut, leaving only a uniform cylinder that could be used to maintain patency to the ventricle.

Modulus Testing

Uniaxial compression (Fig. 4) and shear tests were performed on the gel specimens using an Instron Material Testing System (Model 1321 frame with a Model 8500 controller). All tests were conducted at room temperature. Prior to testing, a small precompression was applied to ensure full contact between the testing fixture and gel specimens.

Force-displacement histories were recorded using a data acquisition system (TDAS-Pro, Diversified Technical Systems, Inc.) at a sampling rate of 1 kHz. Engineering stress was calculated as the ratio of force and nominal area of specimen, and engineering strain was calculated as the ratio of compression/shear displacement and the initial thickness of the specimen. The thickness of each gel sample was measured before testing. The compression velocity was then defined for each sample to allow the same engineering strain rates (0.01/sec, 0.1/sec, and 1/sec). A maximum engineering strain level of 30% was performed during the experiments.

Creation of Mimetic Endoscope

A mimetic endoscope was created using a 5.5-mm bore-scope camera with adjustable LED light (Volador), 8-mm stainless steel drinking straw (MalloMe) for rigid frame, 3D printed PLA handle to hold the device, and molding clay to stabilize the construct (Fig. 3). First, Blender was used to design the endoscope handle. A simple solid cube was chosen from the preexisting shapes available in the

FIG. 2. Brain molds 3D printed in 4 sections to facilitate removal of silicone from mold. Empty molds placed together (A), secured with silk tape to prevent leaking (B), filled with liquid silicone (C), and then allowed to cure overnight (D). Figure is available in color online only.

Blender software and elongated to a more rectangular shape. Next, a simple solid cylinder was selected and the dimensions adjusted to an ideal size for the central space of the endoscope handle. In Blender, a Boolean operation was performed between the rectangle and cylinder, leaving a rectangle with a central canal and thus the desired handle for the endoscope. The file was then exported as an STL file and opened in Meshmixer to inspect for non-

manifold components. The mesh dimensions were resized in Cura so that the central canal measured 8 mm. The size of the handle itself was based on user comfort and did not need to be specific. Once the scaling of the mesh was finalized, the print settings for the PLA filament were selected and the gcode for the 3D printer was created. The gcode was then transferred to the Lulzbot Taz 6 3D printer and the endoscope handle mesh was printed. After the print

FIG. 3. Three-dimensional printed skull and mimetic endoscope. Skull and skull base (A and D), mimetic endoscope with adjustable light source (B and E), and anterior and lateral views of skull with silicone brain (C and F). Figure is available in color online only.

FIG. 4. Silicone brain phantom compression and shearing moduli. Compression (A–D) and shearing (E–H) moduli for silicone/Slacker ratios of silicone only (A and E), 10:5 (B and F), 10:6 (C and G), and 10:7 (D and H) were tested at strain rates of 0.01/sec, 0.1/sec, and 1/sec. Uniaxial compression tests (I) were performed on silicone/Slacker samples of varying ratios using an Instron Material Testing System. Figure is available in color online only.

was completed, an 8-mm stainless steel straw was placed in the central canal with a snug fit. To ensure the stainless steel straw did not move in the handle, molding clay was placed on the proximal and distal ends of where the central canal of the handle meets the stainless steel straw. Next, the 5.5-mm flexible borescope with adjustable LED light at the tip of the camera was placed through the lumen of the stainless steel straw until the camera was just past the distal end of the straw. To secure the borescope camera with the stainless steel straw, black electrician's tape was used at the proximal end (Fig. 3).

Preparation of Ventricular Anatomy

The ventricular anatomy was mimicked using common, affordable supplies (Fig. 5). The choroid plexus was made with an unraveled cotton ball, thalamostriate and septal

veins with butterfly needle tubing filled with blue food coloring, basilar artery with butterfly needle tubing filled with red food coloring, and the mammillary bodies and fornix were filled with silicone. The choroid plexus was kept in place by preparing uncured silicone and applying it to the inferior surface of the cotton. Once cured, the cotton was secure. The fornix was affixed via the same technique used for the cotton of the choroid plexus. The tubing mimicking the thalamostriate and septal veins was secured by creating small sleeves in the silicone in the ventricle to restrict the tubing from moving significantly. The tubing representing the basilar artery was secured by wrapping it circumferentially around the silicone representation of the pons/medulla. The third ventricle floor was created from the plastic ring of a common 16.9-oz plastic water bottle and a single delicate task wipe (Kimwipe, Kimtech). Su-

FIG. 5. ETV simulator anatomical mimetics. Thalamostriate vein and septal vein (A), basilar artery (B), third ventricle floor made of delicate care wipe draped over plastic ring (C), pediatric Foley catheter abutting third ventricle floor (D), perforation of the mimetic third ventricle floor (E), and inflation of Foley catheter with enlargement of the ETV (F). Figure is available in color online only.

perglue was applied to the plastic ring and a single Kimwipe was draped over the ring and the excess Kimwipe cut (Fig. 5). Silicone was used to create a sleeve beneath the third ventricle floor to allow for easy interchanging of the mimetic third ventricle floor after each ETV procedure in the simulator.

ETV Technique

The USB of the mimetic endoscope was plugged into a desktop computer equipped with the free Oasis software

required for live video (<http://www.oasisscientific.com/downloads.html>), compatible with Windows and Android. The ETV simulator was submerged in water to mimic CSF. The endoscope was introduced into the right lateral ventricle and advanced through the foramen of Monro into the third ventricle. A 6-Fr pediatric Foley catheter was introduced into the third ventricle and used to create a defect in the third ventricle floor. The Foley balloon was inflated until the defect in the third ventricle floor was at least 5 mm. The endoscope was then advanced into the prepontine cistern for visualization of the basilar artery.

TABLE 1. Itemized cost of ETV simulator and endoscope mimetic

Equipment or Consumable	Cost (USD)
Lulzbot Taz 6 3D printer	2350.00
PLA filament	5.69
ABS filament	19.70
Ecoflex 00-30 silicone	18.06
Slacker	19.43
Release agent	13.20
5.5-mm borescope	21.99
8-mm stainless steel straw	1.83
Molding clay	3.67
Electrician's tape	2.00
6-Fr Foley catheter	8.95
Butterfly needle tubing	1.82
Food coloring	2.00
10-ml syringe	1.00
Delicate care wipes	2.44
Cotton balls	1.00
Total (excluding 3D printer)	122.78

Total approximate time required was 48 hours, and the approximate involved labor required was 8 hours.

Participants for Evaluation of ETV Simulator With Mimetic Endoscope

Fifteen neurosurgeons from the Wayne State University Department of Neurosurgery participated in the evaluation of the ETV simulator with mimetic endoscope. This cohort consisted of 12 residents (postgraduate years 1–7) and 3 attending physicians. Experience with performing ETV ranged from 0 to > 10 procedures with a median of 6 total ETVs performed. Each participant then performed an ETV using the simulator, followed by a 5-point Likert scale survey.

Results

ETV Model Costs

The skull model with support structures and endoscope handle were 3D printed with PLA filament at a rate of 50 mm/sec, layer height of 0.25 mm, and fill density of 20%, which took just under 14 hours and 25 minutes to 3D print. Printing of the skull model consumed 212 g of PLA and the endoscope handle required 25 g of PLA, corresponding to a cost of US\$5.09 and US\$0.60, respectively, for each model (Table 1).

ABS filament was used to print the 4 sections of the brain mold at a rate of 50 mm/sec, layer height of 0.38

FIG. 6. Comparison of silicone brain phantom compression and shearing moduli to that of brain parenchyma. Silicone brain phantom compression (**A and B**) and shearing (**C and D**) moduli for silicone/Slacker mixtures of 10:6 (**A and C**) and 10:7 (**B and D**) are shown. Brain parenchyma compression (**A and B**) and shearing (**C and D**) moduli at a strain rate of 0.5/sec are shown as red dotted lines. Figure is available in color online only.

mm, and fill density of 20%, which took 28 hours total to 3D print. The brain mold required 896 g of ABS filament, corresponding to a cost of \$19.70. Total costs for the ETV model with endoscope and the tools necessary for the creation of the model were \$122.78 (Table 1).

Shearing and Compression Moduli

Compression and shearing moduli for the silicone brain phantom at silicone/Slacker ratios of 10:7, 10:6, and 10:5, and silicone only were tested and compared to the moduli of human brain parenchyma (Fig. 4). Silicone/Slacker mixtures with ratios of less than 10:7 were not tested as the cured mixtures were too compliant compared with brain parenchyma. In addition, with a decreased proportion of silicone (< 10:7), the mixture becomes increasingly adherent, making it difficult to be removed from the mold. After compression and shearing modulus testing, a silicone/Slacker ratio between 10:6 and 10:7 was found to be closest to that of human brain parenchyma (Fig. 6). A silicone/Slacker mixture of 10:6 was chosen over 10:7 for ease of removal from the brain mold despite the fact that the 10:6 ratio was a little less compliant with regard to shearing modulus. The compression and shearing moduli of the skull model and delicate task wipe were not tested.

Evaluation of ETV Simulator With Mimetic Endoscope

Eighty-seven percent of participants strongly agreed that the ETV simulator was a useful model for resident training, and 93% strongly agreed that the simulator helped them better understand how to orient themselves within the ventricles with the endoscope (Table 2). The mimetic endoscope possessed the appropriate illumination and resolution to adequately navigate the simulated ventricles (87% strongly agreed), helped with eye-hand coordination (80% strongly agreed), helped with depth perception (80% strongly agreed), and provided appropriate tactile feedback (60% strongly agreed). Seventy-three percent of participants strongly agreed that the silicone brain phantom was similar to the properties of human brain parenchyma. The basilar artery, thalamostriate vein, and anterior septal vein were adequately replicated using butterfly needle tubing with food coloring (87% strongly agreed). The wet unraveled cotton ball provided a good choroid plexus mimetic (73% strongly agreed). The wet delicate care wipe (Kimwipe) closely resembled the properties of the third ventricle floor (73% strongly agreed). Free-text comments further commended the mimetic third ventricle floor for its ability to be easily penetrated by the catheter and maintain ventriculostomy size with the expanding balloon of the

TABLE 2. Resident/attending survey results after using ETV simulator with endoscope mimetic (n = 15)

Questions	Strongly Disagree (1)	Disagree (2)	Neither Agree nor Disagree (3)	Agree (4)	Strongly Agree (5)	Mean Score	SD
The wet delicate care wipe (Kimwipe) closely resembled the properties of 3rd ventricular floor	0 (0%)	0 (0%)	0 (0%)	4 (27%)	11 (73%)	4.73	0.46
The wet unraveled cotton ball provided a good choroid plexus mimetic	0 (0%)	0 (0%)	0 (0%)	4 (27%)	11 (73%)	4.73	0.46
The butterfly needle tubing with food coloring was a good thalamostriate vein, anterior septal vein, and basilar artery mimetic	0 (0%)	0 (0%)	0 (0%)	2 (13%)	13 (87%)	4.87	0.35
The silicone brain properties resembled that of human brain parenchyma	0 (0%)	0 (0%)	0 (0%)	4 (27%)	11 (73%)	4.73	0.46
The endoscope mimetic with adjustable light source was well designed and easy to use	0 (0%)	0 (0%)	0 (0%)	2 (13%)	13 (87%)	4.87	0.35
This ETV simulator helped with eye-hand coordination	0 (0%)	0 (0%)	0 (0%)	3 (20%)	12 (80%)	4.80	0.41
This ETV simulator helped with depth perception	0 (0%)	0 (0%)	0 (0%)	3 (20%)	12 (80%)	4.80	0.41
This ETV simulator helped me better understand how to orient myself with the endoscope	0 (0%)	0 (0%)	0 (0%)	1 (7%)	14 (93%)	4.93	0.26
This ETV simulator provided appropriate tactile feedback	0 (0%)	0 (0%)	0 (0%)	6 (40%)	9 (60%)	4.60	0.51
This ETV simulator is a useful model for resident training	0 (0%)	0 (0%)	0 (0%)	2 (13%)	13 (87%)	4.87	0.35

catheter without tearing. The simulator was compared to an actual ETV surgery to show the similarities (Video 1).

VIDEO 1. Clip showing ETV with mimetic endoscope in silicone brain simulator compared to real ETV in human with high-definition operative-grade endoscope. Copyright R. Justin Garling. Published with permission. Click here to view.

Discussion

ETV is a common neurosurgical procedure performed for hydrocephalus secondary to aqueductal stenosis or fourth ventricular outflow obstruction, but it is not without significant risks.^{8,18} Neurosurgical training currently places heavy emphases on surgical milestones in an ever-changing environment focused on patient outcomes.^{3,7} This can lead to novices performing ETV without a high level of confidence with endoscope orientation and intraventricular anatomy, ultimately affecting patient outcome.^{1,12} We developed an ETV simulator that provided a safe, risk-free environment for the development of these crucial surgical skills. Previous ETV simulators for resident training have been cost-prohibitive and have not considered the modulus of elasticity of brain parenchyma.

We have successfully created a cost-effective, reusable ETV simulator and mimetic endoscope for US\$123. Total time required was approximately 48 hours; however, most of the processes are run without active involvement and only approximately 8 hours of labor is required. Current ETV models have been costly when considering the software required to create the simulator and the need for an operating room-grade endoscope with a light source tower.^{2,6,20} Such equipment and resources are not available to the average neurosurgical resident and carry the inherent risk of being damaged with high replacement costs. In this paper we present a method for creating an ETV simulator using free open-source software readily available to the public.^{4,14–16} Creation of an ETV simulator and its constituents without the aid of open-source software requires monthly fees or institutional subscriptions for the

service. To offset the cost of an operative endoscope with light source tower, we used a combination of 3D printing, over-the-counter resources, and a borescope. Flexible borescope technology is affordable (under \$50) for the majority of entry-level scopes. Furthermore, the illumination/resolution of borescopes has been found to be acceptable for retrieving lost items from dark, difficult-to-reach places, and thus deemed suitable for aiding in the development of an ETV simulator.

Brain parenchyma created from resin, silicone, synthetic rubber, and virtual reality has been used in past ETV simulators, but none have accounted for the inherent properties of human brain parenchyma. These simulators relied strictly upon the opinions of the tactile feedback of the material compared to human brain by practicing neurosurgeons. Here, we created a model with quantitatively similar compression and shearing moduli versus human brain parenchyma for which 73% of participants strongly agreed. During ETV, the brain undergoes compression and shearing forces when the endoscope is introduced through the brain parenchyma into the lateral ventricle. When maneuvering the endoscope while in the lateral or third ventricle, compression and shearing forces are transmitted to the cortex being penetrated and the fornix, which constitutes the anterior half of the foramen of Monro. It is crucial to understand what the tactile feedback of the brain parenchyma is and the consequences of excessive movements that may cause damage to the cortex or fornix. Thus, it was important to test compression and shearing moduli in this silicone-based model to recreate the environment and tactile feedback one would experience while maneuvering the endoscope. The silicone/Slacker ratios of 10:6 and 10:7 were found to have compression and shearing moduli closest to that of normal human brain parenchyma. A silicone/Slacker mixture of 10:6 was chosen over 10:7 for ease of removal of the silicone from the brain mold despite the fact that the 10:6 ratio was slightly less compliant with regard to shearing modulus. The control for normal human brain parenchyma was obtained from a study in which 240

postmortem human brain tissue specimens were tested for compression and shearing moduli at several strain rates.¹⁰ Although the strain rates in the current study are relatively low compared with those in the literature, clear viscoelasticity was observed in our silicone/Slacker mixture testing at different strain rates, which represents an important characteristic of human brain parenchyma.

Testing of the compression and shearing moduli of the mimetic third ventricle floor of the ETV simulator was not conducted. Previous ETV simulators used wax paper or silicone to simulate the third ventricle floor. A single delicate care wipe submerged in water was found to provide better tactile feedback for simulating penetration of the third ventricle floor than wax paper and other previously described methods. This was corroborated in the free-text comments section by attending physician participants, who described how similar the delicate care wipe was to the properties of the third ventricle floor. Furthermore, one attending noted how the delicate care wipe could mimic those instances of a thicker third ventricle floor by simply doubling the thickness. However, formal delicate care wipe modulus testing was not completed due to lack of an optimal human third ventricle floor control.

Modulus testing and altering the properties of silicone have applications to an array of surgical models outside of ETV and are the topics of future work in our lab. Manipulation of the silicone/Slacker ratio could be useful in the creation of brain tumor models. Varying the properties of silicone could allow for the mimicking of tumors with different densities. Testing of the modulus of the skull would allow for the creation of surgical models that assist with proper drilling techniques. Furthermore, the moduli of the skull could be used to aid in the 3D printing of simulators for teaching complex drilling techniques needed during skull base approaches.

To improve our ETV simulator, future models will address the lack of a closed ventricular system and CSF flow. Biaxial testing would be an interesting modality that we could pursue in future work when such data on human brain tissue are available for comparison. To counter the limitations of a silicone-based model, future work in our lab has focused on an agarose brain model. Similar to a silicone/Slacker mix, agarose provides a low-cost, reusable medium that possesses similar compression and shearing moduli to human brain parenchyma. However, agarose is much more fragile than silicone and may not be suitable for the needs of some simulators.

Conclusions

We successfully created a low-cost (\$123, excluding 3D printer), easy-to-use, silicone-based ETV simulator and mimetic endoscope for resident training purposes using free open-source software (87% of participants strongly agreed). Previous simulators made from resin, silicone, virtual reality, and synthetic rubber did not account for the modulus of elasticity of brain parenchyma and relied upon expensive operative neuroendoscopes with costly light towers.^{2,5,6} Such equipment may not be readily available to the average neurosurgical resident and carries the inherent risk of being damaged with prohibitive repair costs.

The most expensive and cost-prohibitive item in our ETV simulator was the up-front cost of the 3D printer. Many institutions and larger universities with residency programs have begun to adopt 3D printer technology. Collaboration between departments may help minimize costs for programs looking to develop surgical models without incurring initial 3D printer costs. Our inexpensive method for printing ETV simulator constituents allows for the development of crucial surgical milestones in a safe, risk-free environment. The low-cost 0° endoscope we have presented in conjunction with a 3D printing technique has utility in an array of neurosurgical endeavors. Future projects include endoscopic skull base approaches, an agarose brain model, and endoscopic device development.

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Disclosures

The authors report no conflict of interest concerning the materi-

als or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Garling, Harris. Acquisition of data: Garling. Analysis and interpretation of data: all authors. Drafting the article: Garling, Harris. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Garling. Administrative/technical/material support: all authors. Study supervision: Harris.

Supplemental Information

Videos

Video 1. <https://vimeo.com/259169615>.

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