Creation of a novel simulator for minimally invasive neurosurgery: fusion of 3D printing and special effects

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OBJECTIVE Recent advances in optics and miniaturization have enabled the development of a growing number of minimally invasive procedures, yet innovative training methods for the use of these techniques remain lacking. Conventional teaching models, including cadavers and physical trainers as well as virtual reality platforms, are often expensive and ineffective. Newly developed 3D printing technologies can recreate patient-specific anatomy, but the stiffness of the materials limits fidelity to real-life surgical situations. Hollywood special effects techniques can create ultrarealistic features, including lifelike tactile properties, to enhance accuracy and effectiveness of the surgical models. The authors created a highly realistic model of a pediatric patient with hydrocephalus via a unique combination of 3D printing and special effects techniques and validated the use of this model in training neurosurgery fellows and residents to perform endoscopic third ventriculostomy (ETV), an effective minimally invasive method increasingly used in treating hydrocephalus.

METHODS A full-scale reproduction of the head of a 14-year-old adolescent patient with hydrocephalus, including external physical details and internal neuroanatomy, was developed via a unique collaboration of neurosurgeons, simulation engineers, and a group of special effects experts. The model contains “plug-and-play” replaceable components for repetitive practice. The appearance of the training model (face validity) and the reproducibility of the ETV training procedure (content validity) were assessed by neurosurgery fellows and residents of different experience levels based on a 14-item Likert-like questionnaire. The usefulness of the training model for evaluating the performance of the trainees at different levels of experience (construct validity) was measured by blinded observers using the Objective Structured Assessment of Technical Skills (OSATS) scale for the performance of ETV.

RESULTS A combination of 3D printing technology and casting processes led to the creation of realistic surgical models that include high-fidelity reproductions of the anatomical features of hydrocephalus and allow for the performance of ETV for training purposes. The models reproduced the pulsations of the basilar artery, ventricles, and cerebrospinal fluid (CSF), thus simulating the experience of performing ETV on an actual patient. The results of the 14-item questionnaire showed limited variability among participants' scores, and the neurosurgery fellows and residents gave the models consistently high ratings for face and content validity. The mean score for the content validity questions (4.88) was higher than the mean score for face validity (4.69) ($p = 0.03$). On construct validity scores, the blinded observers rated performance of fellows significantly higher than that of residents, indicating that the model provided a means to distinguish between novice and expert surgical skills.

CONCLUSIONS A plug-and-play lifelike ETV training model was developed through a combination of 3D printing and special effects techniques, providing both anatomical and haptic accuracy. Such simulators offer opportunities to accelerate the development of expertise with respect to new and novel procedures as well as iterate new surgical approaches and innovations, thus allowing novice neurosurgeons to gain valuable experience in surgical techniques without exposing patients to risk of harm.

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KEY WORDS endoscopic third ventriculostomy; 3D printing technology; minimally invasive neurosurgery; hydrocephalus; simulation; surgical trainers; residency

ABBREVIATIONS ACGME = Accreditation Council of Graduate Medical Education; CSF = cerebrospinal fluid; ETV = endoscopic third ventriculostomy; OSATS = Objective Structured Assessment of Technical Skills; PGY = postgraduate year.

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RAPID advances in optics, miniaturization, and computer technology have opened the door to a new field of minimally invasive neurosurgery.^{1,6,16,17,38} Selected procedures are now being performed through smaller surgical exposures using an array of microinstruments under endoscopic guidance, thereby reducing trauma to the brain and expediting patient recovery. Endoscopic third ventriculostomy (ETV) has evolved to become the treatment of choice in selected cases of noncommunicating hydrocephalus. Although this and other neuroendoscopic procedures are minimally invasive, they are not risk free and may be associated with major morbidity and mortality.^{15,18,19,41,42}

Recently, the neurosurgical community has been forced to rethink surgical training. Since the implementation of duty-hour restrictions by the Accreditation Council of Graduate Medical Education (ACGME), trainees have less exposure to operative cases during their residency years.^{12,22,29,30} Multiple studies have described the benefits of simulation in the acquisition of technical skills, as a means to complement operative training,^{5,19,31,32,43,44,51,52} but there is currently no effective model that functionally simulates the condition being treated and can serve as a learning tool to allow neurosurgeons in training to practice minimally invasive neurosurgical procedures before performing these procedures on actual patients.^{24,29,35,40}

3D printing technology has recently been demonstrated to be a powerful tool for presurgical planning, rehearsal, and decision making.^{4,14,33,45,50} The technology has the further potential to improve training by enabling the creation of models that provide excellent detail for both normal and pathological anatomy and are reliable, reusable, cost-effective, and most importantly, realistic.^{36,50} Unfortunately, however, the resins currently used in 3D printing are relatively stiff, so even though the resulting models provide excellent anatomical detail, their lack of haptic, or tactile, feedback limits their effectiveness in simulating an actual surgical experience. Hollywood special effects techniques can overcome this limitation by combining a variety of materials that ultimately create ultrarealistic features to enhance accuracy and effectiveness of the surgical models.

In an attempt to improve current simulators and to address training challenges, we hypothesized that a combination of 3D printing technology and special effects techniques and materials could produce a highly realistic and relevant training model for practicing ETV and that the model could be validated for face, content, and construct validity. The model could then be embedded in a proposed program, where it provides a novel method for training in minimally invasive neurosurgery with the ultimate goal of enhancing patient safety.

Methods

This research study was approved by the institutional review board of Boston Children's Hospital. The study was divided into 2 parts: 1) the creation of a hydrocephalus model for the performance of ETV and 2) validation of the model for neurosurgical education.

Creation of the ETV Training Model and Simulator

Deidentified MRI studies that had been originally obtained in a 14-year-old adolescent with noncommunicating hydrocephalus were used to develop patient-specific models of the anatomical components involved in the ETV procedure. Based on data from the original studies, the corresponding skull and intracranial structures were created. Digital Imaging and Communications in Medicine (DICOM) images were converted into standard 3D file format (StereoLithography file, STL). The STL files were translated into code for 3D printing (Fig. 1).

3D prints were used to construct molds, which were provided to Hollywood special effects technicians (FracturedFX, Inc., Hollywood, California) for casting and sculpting of the external components of the training models (Fig. 2). Intracranial structures were reproduced and anatomically embedded into the training models (Fig. 3). The ETV procedure, by definition, creates a hole in the third ventricular floor, rendering it unusable for more than one case. Therefore, we fashioned a series of disposable third ventricular floor membranes for use in a "plug-and-play" fashion. Over an approximately 12-month development period, several versions of the

FIG. 1. Original MRI study and imaging segmentation for the creation of the hydrocephalus model based on 3D printing technology. **A:** Sagittal FIESTA (fast imaging employing steady-state acquisition) MR image obtained in a 14-year-old girl with fourth ventricle outlet obstruction. **B:** Imaging segmentation of the ventricular system from the original MRI studies. **C:** Imaging segmentation from the original files and creation of the brain surface and ventricles for 3D printing. Figure is available in color online only.

FIG. 2. ETV trainer assembly based on 3D printing technology and casting process. **A:** 3D printed brainstem, basilar artery and its branches, and arachnoid membranes. **B:** Superior view of the right lateral ventricle. **C:** ETV trainer without the 3D printed skull and skin covering. Figure is available in color online only.

ETV simulator were created and tested for visual and haptic (tactile) reliability. Although the training models had the same intracranial features, coverings with low and high fidelity to real-life patients were developed for further comparison (Fig. 4). The high-fidelity coverings had more lifelike features, such as skin tone, freckles, hair, eyelashes, and eyebrows.

Validation of the ETV Training Model and Simulator

A simulation-based training program was conducted for neurosurgery fellows and residents of different training levels. After signing consent forms, program participants were randomly paired and assigned to training stations. Individuals were randomly assigned to perform

the procedure either on the training model with ultrarealistic external and facial features or on the anatomical ETV simulators with lower-resolution external landmarks.

Assessment was performed by the neurosurgical training participants, who rated the appearance of the training model (face validity) and the reproducibility of the procedure on the trainer (content validity), and by neurosurgeon graders, who rated the effectiveness of the surgical model (construct validity). The participants who used the training model completed a 14-item Likert-like questionnaire after the procedure. The first 9 questions were related to the face validity and the remaining 5 were related to the content validity (Table 1).^{21,23,25,28,34} Procedures performed

FIG. 3. ETV performed on the simulator using a 0° endoscope lens. **A:** Visualization of the foramen of Monro from the right lateral ventricle; identification of the septal and thalamostriate vessels and choroid plexus. **B:** Visualization of the floor of the third ventricle; identification of the fornix, mammillary bodies, and tuber cinereum. **C:** Close-up visualization of the mammillary bodies and tuber cinereum. **D:** Fogarty balloon catheter with stylet in place to fenestrate the third ventricle floor. **E:** Widening of fenestration by inflation and deflation of the balloon catheter. **F:** Opening in the third ventricle floor and visualization of the basilar artery and interpeduncular cistern. Figure is available in color online only.

FIG. 4. Simulated surgical training model for ETV. **Left:** Low-fidelity ETV model. **Right:** High-fidelity surgical training model. Note the realistic human-like external features, including hair, eyelashes, and eyebrows. Figure is available in color online only.

on the simulators by the neurosurgical fellows and residents were video recorded. Two neurosurgeons who were blinded to participant identity watched the videos and graded the participants' performance, and these grading results were used to assess construct validity based on the Objective Structured Assessment of Technical Skills (OSATS) scale (Table 2).³⁶ The OSATS scale is used to assess the performance of trainees on a variety of structured procedural tasks. The assessment is based on 7 parameters: 1) respect for tissue, 2) time and motion, 3) instrument handling, 4) knowledge of instruments, 5) flow of operation, 6) use of assistants, and 7) knowledge

of the specific procedure. Each parameter is graded on a scale of 1 (lowest score) to 5 (highest score).³⁶ Trainees being tested were not actively supervised by the authors. Such an assessment provides information on the ability and sensitivity of the training model ETV simulator for use in evaluating the performance of the trainees at different levels of experience, discriminating a novice from an expert.^{25,28}

MINOP Modular Neuroendoscopy Systems (Aesculap) were used for the performance of ETV, and 4-Fr Fogarty balloon catheters (Edwards LifeSciences) were used to create the fenestration in the floor of the third ventricle.

Statistical Analysis

Descriptive statistics were computed to summarize results of ratings for the face and content validity questions. A sample size of 16 was calculated by a statistician (P.W.F.) as necessary to determine a minimally significant difference between groups. For the face and content validity questionnaire data, a single generalized estimating equation (GEE) regression model, a model accounting for the correlated nature of repeated measures on a subject, was used to test for effects on rating of the following: training (fellow vs resident), question type (face validity vs content validity question), and model fidelity (high vs low). ANOVA was used to compare the surgical skill of fellows and residents based on OSATS ratings. ANOVA was also used for comparisons between 3 levels of training: fellows, senior residents, and junior residents. For the analysis using the 3 levels of training, a Tukey adjustment

TABLE 1. Face and content validity questionnaire

Face Validity					
<i>Preoperative setup</i>	1	2	3	4	5
1. External landmarks	Poorly reproduced		Somewhat realistic		Realistically reproduced
<i>Ventricles</i>	1	2	3	4	5
2. Foramen of Monro	Poorly reproduced		Somewhat realistic		Realistically reproduced
3. Floor of the 3rd ventricle	Poorly reproduced		Somewhat realistic		Realistically reproduced
4. Interpeduncular cistern	Poorly reproduced		Somewhat realistic		Realistically reproduced
<i>Motion</i>	1	2	3	4	5
5. CSF flow in the ventricles	Poorly reproduced		Somewhat realistic		Realistically reproduced
6. Pulsations of the floor of the 3rd ventricle	Poorly reproduced		Somewhat realistic		Realistically reproduced
7. Pulsations of the basilar artery	Poorly reproduced		Somewhat realistic		Realistically reproduced
<i>Overall</i>	1	2	3	4	5
8. Tactile feedback	Poorly reproduced		Somewhat realistic		Realistically reproduced
9. Overall tissue properties	Poorly reproduced		Somewhat realistic		Realistically reproduced
Content Validity					
<i>This trainer is effective in:</i>	1	2	3	4	5
10. Providing a means to navigate in the ventricles	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
11. Providing eye-hand coordination	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
12. Improving depth perception	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
13. Reproducing the ETV procedure	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
14. Adequately fenestrating the tuber cinereum	Strongly disagree	Disagree	Neutral	Agree	Strongly agree

Questions 1–9 assess face validity and questions 10–14 assess content validity.

TABLE 2. Mean scores for face and content validity based on the participants' evaluations

Evaluation	Mean	SD	Median	Min	Max
Face validity					
1. External landmarks	4.76	0.56	5.00	3.00	5.00
2. Foramen of Monro	4.88	0.33	5.00	4.00	5.00
3. Floor of the 3rd ventricle	4.82	0.39	5.00	4.00	5.00
4. Interpeduncular cistern	4.88	0.33	5.00	4.00	5.00
5. CSF flow in the ventricles	4.18	0.88	4.00	3.00	5.00
6. Pulsations of the floor of the 3rd ventricle	4.53	0.80	5.00	3.00	5.00
7. Pulsations of the basilar artery	4.59	0.71	5.00	3.00	5.00
8. Tactile feedback	4.53	0.80	5.00	3.00	5.00
9. Overall tissue properties	4.65	0.70	5.00	3.00	5.00
Content validity					
10. Providing a means to navigate in the ventricles	4.88	0.33	5.00	4.00	5.00
11. Providing eye-hand coordination	4.88	0.33	5.00	4.00	5.00
12. Improving depth perception	4.82	0.39	5.00	4.00	5.00
13. Reproducing the ETV procedure	4.76	0.44	5.00	4.00	5.00
14. Adequately fenestrating the tuber cinereum	4.82	0.39	5.00	4.00	5.00

Max = maximum; min = minimum.

was used to correct for multiple comparisons when making post hoc pairwise comparisons between groups. Pearson correlation coefficients and weighted kappa statistics were used to assess rater agreement for the OSATS questions. SAS version 9.3 was used for all analyses, and an alpha of 0.05 was considered the threshold for statistical significance.

Results

Surgical Training Model and Simulator

An interactive approach was taken from prototype to final version of a high-fidelity patient-specific hydrocephalus model for the performance of ETV via a combination of 3D printing and special effects methods and technologies. All participants in the study described the resulting training models as providing an effective simulation of the surgical procedure. External anatomical landmarks, including sagittal and coronal sutures, and internal neuroanatomy, such as the foramen of Monro, anterior septal and thalamostriate veins, choroid plexus, fornix, and mammillary bodies, were accurately reproduced. A manual water pump was used to reproduce the CSF flow and the pulsations inside the ventricular cavities, choroid plexus, basilar artery, and floor of the third ventricle. Subsequently, we developed an electronic pump for this purpose.

For the reproducibility of the ETV procedure on the simulator, the floor of the third ventricle provided accurate texture for the fenestration and dilation of the tuber cinereum using a 4-Fr Fogarty balloon catheter. CSF flow

TABLE 3. Mean performance scores based on the OSATS scale

OSATS Item	Fellows (n = 4)	Residents (n = 13)	p Value
Respect for tissue	4.00	2.85	0.0130
Time and motion	4.75	2.46	0.0004
Instrument handling	4.50	2.77	0.0033
Knowledge of instruments	4.75	3.23	0.0038
Flow of operation	4.50	2.52	0.0004
Use of assistants	4.75	2.77	<0.0001
Knowledge of specific procedure	4.50	2.62	0.0004

For the analysis, the participants were grouped in fellows and residents.

through the fenestration of the floor of the third ventricle was reproduced (Video 1).

VIDEO 1. ETV performed on a patient-specific 3D printed simulator. Copyright Alan R. Cohen. Published with permission. Click here to view.

Validation

We conducted a validation of this simulation model by examining the performance of neurosurgery residents and fellows on the trainer. Seventeen participants were enrolled; the group included 13 residents at different levels of training and 4 neurosurgery fellows.

Based on a 14-item questionnaire to assess face and content validity, there was limited variability among participants' evaluations, and the ratings were consistently high (Table 2). The mean score for the content validity questions (4.88) was statistically higher than the mean score for face validity (4.69) ($p = 0.03$). Fellows' scores were on average 0.35 points higher than residents' scores ($p < 0.0001$). The difference in mean scores between high- and low-fidelity trainers was not statistically significant ($p = 0.957$).

To assess construct validity, 2 neurosurgeons who were blinded to participant identity rated the performance of ETV by using the OSATS scale. For each measure, the fellows' ratings were significantly higher than those of the residents, indicating a more advanced training level, better knowledge of the operative instruments, and greater surgical experience (Table 3). Comparison of the mean scores of the junior (postgraduate year [PGY] 1–3) and senior (PGY 4–7) resident groups showed that the senior residents had significantly higher scores for time and motion ($p = 0.0314$) and instrument handling ($p = 0.0037$). Pairwise senior versus junior resident comparisons showed a nonsignificant trend toward superior performance for senior residents in both respect for tissue ($p = 0.053$) and use of assistants ($p = 0.053$) (Table 4). Weighted kappa agreement statistics on the evaluation of the performance of the participants showed consistently high agreement scores between raters (Table 5).

Discussion

This unique collaboration among neurosurgeons, simulation engineers, and 3D printing special effects experts resulted in the creation of a novel lifelike hydrocephalus

TABLE 4. Means of performance scores based on the OSATS scale

OSATS Item	Fellow (n = 4)	Senior Resident (n = 5)	Junior Resident (n = 8)	p Value*	Significant Pairwise Comparisons
Respect for tissue	4.0 (0)	3.4 (0.5)	2.5 (0.8)	<0.01	Fellow > junior
Time & motion	4.8 (0.5)	3.2 (0.8)	2.0 (0.8)	<0.001	All 3 differ significantly
Instrument handling	4.5 (0.6)	3.6 (0.5)	2.3 (0.7)	<0.001	Fellow & senior > junior
Knowledge of instruments	4.8 (0.5)	4.0 (0.7)	2.8 (0.5)	<0.001	Fellow & senior > junior
Flow of operation	4.5 (0.6)	3.0 (0.7)	2.4 (0.7)	<0.001	Fellow > senior & junior
Use of assistants	4.8 (0.5)	3.2 (0.4)	2.5 (0.5)	<0.001	Fellow > senior & junior
Knowledge of specific procedure	4.5 (0.6)	3.0 (0.7)	2.4 (0.7)	<0.001	Fellow > senior & junior

* For overall tests.

model to improve training for ETV. The combination of 3D printing technology to create accurate anatomical detail and casting/molding processes to add lifelike tactile and visual physical features provided a means to develop accurate pediatric surgical trainers capable of mimicking a live procedure in a safe environment, without risk of patient harm.

The ETV procedure has gained popularity among neurosurgeons as an effective minimally invasive method for treating selected cases of hydrocephalus. Minimally invasive techniques require a new skill set, including task-specific eye-hand coordination and psychomotor skills.^{1-3, 6-8,16,18,20,26,37,38,46,47}

Simulation-based education provides a means to assist trainees in developing technical skills and improving operative performance.

Existing methods for surgical training in minimally invasive neurosurgery include didactic lectures, video demonstrations, and hands-on courses using cadavers, physical models, and virtual reality platforms. During teaching seminars, trainees are often asked to watch video presentations and are unable to participate in hands-on training. Cadavers have been considered the gold-standard teaching models for years. However, this approach is intrinsically flawed;^{10,39} neurosurgical procedures are conducted for pathological disorders, yet human specimens rarely reflect those conditions. Current physical prototypes are low fidelity and even less effective as simulators of live patients. Virtual reality systems are expensive and can often lack realism/reliability and haptic feedback.^{13,14,19} Therefore, there is a need for developing effective neurosurgical simulators to complement and improve surgical education.

By combining 3D printing technology and special effects expertise, we created an ultrarealistic surgical simulator for training neurosurgeons to perform ETV in a pediatric patient. The special effects expertise was crucial in the process of refining the training model artistically and creating lifelike tissue properties. We added several features that significantly enhanced the realism of the simulator, including the pulsation of the ventricular cavities, pulsation of the basilar artery, and flow of CSF.

Our 3D printed model of hydrocephalus provides a means to simulate operative techniques in a stepwise process. The model enables the participants to plan the surgical approach, position the patient, navigate within the ventricles, and develop psychomotor coordination for the performance of ETV. Our surgical model has definite advantages over a virtual reality simulation, which involves a predetermined video program. Also, the surgical tools used in virtual reality are training specific in design and differ from instruments used in the operating room.

Haptic (tactile) feedback is an important factor in simulation-based training. Virtual reality systems transmit vibrations and other sensations to the trainee via a software controller, which often does not accurately reproduce the surgical experience. We were able to reproduce lifelike intracranial features and textures in our simulator. Such features and textures enable the trainees to experience haptic feedback that accurately simulates what they would experience in performing the real procedure.

The effectiveness and reliability of the ETV trainer were assessed based on face, content, and construct validity. Haji et al.²⁷ conducted a national survey on assessment tools for simulation in neuroendoscopy. Based on their

TABLE 5. Rater agreement of performance grading based on the 7-item OSATS scale

OSATS Scale	% Complete Agreement	Correlation Coefficients (p value)	Kappa (95% CI)
Respect for tissue	90%	0.968 (<0.0001)	0.911 (0.758–1.000)
Time & motion	90%	0.977 (<0.0001)	0.936 (0.810–1.000)
Instrument handling	60%	0.862 (0.0013)	0.688 (0.442–0.933)
Knowledge of instruments	70%	0.930 (<0.0001)	0.563 (0.255–0.870)
Flow of operation	100%	1.000 (<0.0001)	1.000
Use of assistants	90%	0.969 (<0.0001)	0.914 (0.766–1.000)
Knowledge of specific procedure	100%	1.000 (<0.0001)	1.000

Agreement of Observers 1 and 2. Both observers were neurosurgeons blinded to participant identity and level of experience.

study, a Likert-like scale was developed to assess face and content validity, and the participant assessment results indicated that the training models effectively simulated the surgical procedure.

There is currently no effective tool designed specifically to assess construct validity in neuroendoscopy. The OSATS scale, which has been validated in general surgery for the assessment of technical skills, was used to evaluate neuroendoscopic procedures. The operative performance of a novice was distinguished from the performance of an expert based on construct validity. Overall, the novel ETV trainer proved to be a realistic and reliable simulator for operative training.

In the process of developing the ETV simulators, we focused on creating realistic, reliable, reproducible, and cost-effective surgical models. Furthermore, we added highly realistic human-like external features to our models. To manage manufacturing costs, the simulators were designed to have interchangeable plug-and-play components. Use of these components reduces the setup time between trainings, reduces overall costs of the simulators, and makes them reusable.

3D printing technology has introduced a novel strategy to develop effective trainers to reproduce surgical conditions.⁴⁷ Other investigators have used 3D printing technology to create an ETV simulator.^{11,49} We believe that further advances in this technology will provide a means to print highly accurate components of the surgical trainer in an automated fashion, thus reducing cost as well as the time and effort required to assemble the models.^{9,48,50} We estimate that the cost of the lifelike ETV training model and simulator will be less than that of a cadaveric specimen. Because of the problems of cadaveric fixation, we believe that the model we developed can provide a more realistic simulation of the ventricular anatomy. Another advantage of our model is that the plug-and-play component technology allows for reuse.

A potential limitation of this study is that it remains unclear how well the training experience on the ETV simulator will translate into the acquisition of technical skills for real-life procedures. Our model provides an accurate reproduction of the anatomy and pathology encountered at surgery, along with realistic haptic feedback for the trainee. A construct validity analysis shows that our model can distinguish between a novice and expert, but future studies are needed to show whether an expert skill level attained by a surgical trainee performing a simulation, however lifelike, will lead to enhanced competency in the actual operating room. Another limitation of our trainer is that of cost. Although the plug-and-play technology provides a means to replace the used components during simulation, permitting an overall reduction in costs, future iterations with perhaps lower external fidelity may reduce costs further. We are in the process of investigating that possibility. A third limitation of this model is that it includes only one pathological condition, hydrocephalus. Exchangeable components, intended to increase the range of conditions simulated, are currently under development. Although our special effects team was able to create extremely realistic external facial features for the high-fidelity model, this model was not found to

be statistically superior to our low-fidelity training model. Because the high-fidelity simulator is more expensive to produce, its use might be best reserved for selected circumstances, such as to facilitate suspension of disbelief during full team training.

The relevance of such a simulator consists in providing a means for trainees to be involved with the steps of the operative procedure in a risk-free environment. Overall, this method offers opportunities to redesign medical education, incorporating a more focused and safe training strategy. Ultimately, it should provide a means to transfer the surgical skills acquired during simulation to the operative setting, thus potentially decreasing procedure-related complications and optimizing patient safety.

Conclusions

High-fidelity patient-specific training models for the performance of minimally invasive neurosurgical techniques such as ETV can be constructed with anatomical, cosmetic, and haptic accuracy through a combination of 3D printing, simulation engineering, and special effects technologies. These novel simulators offer opportunities to provide improvement and perhaps new paradigms in surgical education through deliberative operative experiences and practice within risk-free environments.

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Author Contributions

Conception and design: all authors. Acquisition of data: Cohen, Rehder. Analysis and interpretation of data: Cohen, Weinstock,

Rehder, Prabhu, Forbes. Drafting the article: Cohen, Weinstock, Rehder. 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: Cohen. Statistical analysis: Forbes. Administrative/technical/material support: Cohen, Weinstock, Rehder, Prabhu, Roussin. Study supervision: Cohen, Weinstock, Rehder.

Supplemental Information

Videos

Video 1. <https://vimeo.com/201683993>.

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