Improving outcomes in pediatric endoscopic third ventriculostomy through outcome analysis and surgeon training

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Chapter 6

Design and evaluation of a new synthetic brain simulator for endoscopic third ventriculostomy

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Abstract

Object

Endoscopic third ventriculostomy (ETV) is an effective but technically demanding procedure with significant risk. Current simulators, including human cadavers, animal models, and virtual reality systems, are expensive, relatively inaccessible, and can lack realistic sensory feedback. The purpose of this study was to construct a realistic, low-cost, reusable brain simulator for ETV and evaluate its fidelity.

Methods

A brain silicone replica mimicking normal mechanical properties of a 4-month-old child with hydrocephalus was constructed, encased in the replicated skull, and immersed in water. Realistic intraventricular landmarks included the choroid plexus, veins, mammillary bodies, infundibular recess, and basilar artery. The thinned-out third ventricle floor, which dissects appropriately, is quickly replaceable. Standard neuroendoscopic equipment including irrigation is used. Bleeding scenarios are also incorporated. A total of 16 neurosurgical trainees (Postgraduate Years 1–6) and 9 pe- diatric and adult neurosurgeons tested the simulator. All participants filled out pediatric (5-point Likert-type items) to rate the simulator for face and content validity.

Results

The simulator is portable, robust, and sets up in minutes. More than 95% of participants agreed or strongly agreed that the simulator's anatomical features, tissue properties, and bleeding scenarios were a realistic representation of that seen during an ETV. Participants stated that the simulator helped develop the required hand-eye coordination and camera skills, and the training exercise was valuable.

Conclusions

A low-cost, reusable, silicone-based ETV simulator realistically represents the surgical procedure to trainees and neurosurgeons. It can help them develop the technical and cognitive skills for ETV including dealing with complications.

Introduction

The development of high levels of technical competence and excellent decision-making skills is a key goal of all neurosurgical residency training programs. Integral to this development is the exposure of residents to a large and diverse number of operative cases.[13] However, over the past 10 years, there has been a significant decline in operative case volumes during residency.[19] Many factors have contributed to this trend, including resident work hour restrictions, changes in disease management, rapid techno- logical advancement, increased subspecialization, demand for more time- and technological practices, and increased demand for patient safety.[11,19–21]

Because of these challenges, there has been an increased interest in using models and simulators for neurosurgical education.[21,22,26] An ideal procedure for simulation training is endoscopic third ventriculostomy (ETV). Although ETV is an effective and widely accepted treatment for obstruc- tive hydrocephalus,[9,23,29] it is technically challenging and carries the risk for serious errors, such as getting lost or disoriented and being unfamiliar with or unable to use the equipment, and technical complications, such as making an inadequate ventriculostomy or causing a basilar artery, hypothalamic, cranial nerve, or forniceal injury.[4] Simulators create a risk-free environment in which residents can learn the basic neurosurgical skills that better prepare them for the actual operating room experience.[21,22,26]

Various training models have been used for neurosurgical training, including human cadavers, live animals, virtual reality, and synthetic phantoms. These models have been used to simulate both open transcranial and minimally invasive neurosurgical procedures.[1–3,5–8, 10,12,14,15,17,18,24,25,30] Human cadaver and animal models provide high fidelity and allow residents to practice entire operations. However, they are expensive, difficult to obtain, raise ethical concerns, require special facilities and personnel, lack tissue properties that closely resemble living human brain tissue, and cannot simulate ventriculo-megaly.[1,5,8,10,30] Virtual reality platforms are reusable and allow for accurate measurement of resident performance but are expensive, are difficult to maintain, lack convinc- ing haptic feedback and visualization, and do not allow the use of actual convincing instruments.[2,3,6,14,15,17,24,25] Synthetic phantom models have shown increasing

promise as effective simulators for neurosurgical training.[7,12,18] Such models are inexpensive, portable, and reusable and allow for the use of actual surgical instruments. However, they lack realistic tissue properties, are not patient specific, and cannot simulate complex and dynamic operations that require critical thinking and decision-making skills and measures to avoid and mitigate complications. To address these needs, we have developed and evaluated a low-cost, reusable, and patient-specific synthetic simulator that can be used to increase familiarity with the camera skills, endoscopic instruments, and hand-eye coordination required to successfully perform an ETV.

Methods

This study was carried out in 2 parts. Part I involved the design and construction of a synthetic brain simulator for ETV. Part II involved the evaluation of the simulator's face and content validity based on feedback from neurosurgery residents, fellows, and attending staff at the University of Toronto.

Part I: Design and Construction of the ETV Simulator

Overview of the Simulator's Features

Haji et al.[17] conducted a needs assessment for simulation training in neuroendoscopy and identified the fol- lowing features as the most important to simulate: 1) in- strument setup, 2) following of cortical entry/trajectory, 3) insertion of the instrument into the ventricles, 4) navigation within the ventricles, 5) selection of the ventriculostomy site, 6) performing the fenestration, 7) confirming ad- equacy of the ventriculostomy, and 8) removing the endoscope and inspecting adequacy fornix. All of these features have been incorporated into our simulator.

Construction of the ETV Simulator

The preoperative CT and MRI studies obtained in a 4-month-old child with hydrocephalus secondary to a pineal tumor were obtained with permission from the parents. All images were de-identified and were stored on the hospital's secure server to maintain patient confidentiality.

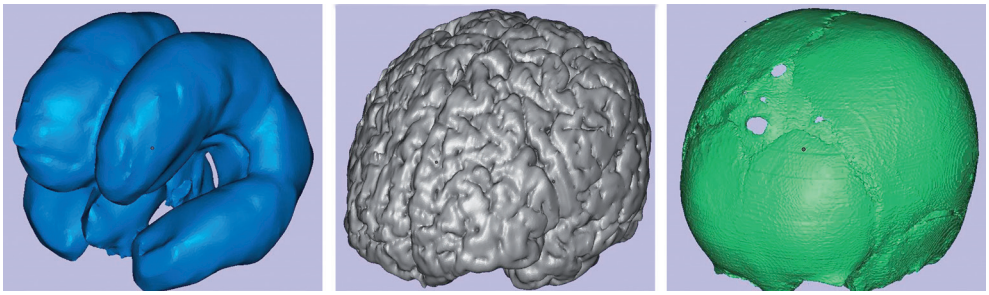

Figure 1. Digital 3D surface molds of the ventricles, brain, and skull generated from the preoperative CT and MRI of a 4-month patient with hydrocephalus using image processing and modeling software.

The preoperative CT and MRI images (DICOM format) were segmented using Mimics (Materialise NV), a commercial image-processing software, to produce 3D surface models of the brain, ventricles, brainstem, pre- pontine cistern, and the skull (Fig. 1). Using Magics (Ma- terialise NV), a commercial modeling software, the 3D surface models were edited to eliminate imperfections from the segmentation process and to generate brain and brainstem molds using the principles of negative space. The generated models were split in half along the midsagittal plane and were then saved in the stereolithography file format. The models were then printed using a Spectrum Z510 3D printer (Z Corp.).

The printed ventricular system model (lateral and third ventricles) was used to create a "negative" silicone mold of the ventricles. This mold was then used to produce a clay model of the ventricles that exactly replicated the printed model. This was done to ensure easy extraction of the ventricle model once the final brain model was completed. The prepontine cistern was created in a similar way To create the brain and brainstem, Dragon Skin liquid silicone (Smooth-On, Inc.) was used to cast the negative molds. The mechanical properties of the silicone were adjusted by adding Slacker (Smooth-On, Inc.), a softener that allows the silicone to closely resemble brain tissue. Based on volume, we used a 2:1 mix ratio of silicone to Slacker. The clay ventricular and printed prepontine cistern models were appropriately positioned within one- half of the brain mold. The silicone/Slacker mixture was then poured into the mold and cured for 16 hours. The second half of the mold was then filled with the silicone/ Slacker mixture, and the first hemisphere was positioned on top so that the 2 hemispheres would merge together once the silicone cured. The "brain" was removed from both

halves of the mold as a single piece. The clay ventricular model and printed prepontine cistern model were then extracted leaving the brain with an open ventricular system and prepontine cistern within which the brainstem and basilar artery could be placed.

The anterior septal and thalamostriate veins, mammillary bodies, and infundibular recess were then added by hand using appropriately colored silicone. The basilar artery was created by layering red silicone over a 3D printed model of the vessel lumen. The basilar artery was then attached to the anterior surface of the brainstem. The choroid plexus was created using red foam and it was positioned within the choroid fissure of the lateral ventricles. The layer of silicone within the third ventricle floor located between the infundibular recess anteriorly and mammillary bodies posteriorly was removed. The floor was then reconstructed using wax paper supported on a plastic ring to simulate the thinned-out floor of the third ventricle. The dimensions of the floor were based on previously reported cadaveric studies.[27] This type of floor was easily replaced after each ventriculostomy.

Bleeding scenarios were incorporated within the simulator to train surgeons how to manage them appropriately. Silicone tubing was inserted into the choroid plexus and at the tip of the basilar artery. Simulated blood (milk with red food coloring) was injected from a 10-ml syringe via hid- den tubing by the simulation monitor to simulate bleeding from the choroid hidden or a basilar artery injury. The final brain model was placed within the 3D print- ed skull model with a predrilled right frontal bur hole located 1 cm anterior to the printed coronal suture along the mid- pupillary line. The brain and skull were stabilized in a custom-made skull holder and placed into a water-filled container.

Part II: Evaluation of the Face and Content Validity of the ETV Simulator

Participants and Data Collection

Residents (Postgraduate Year [PGY] 1–6), fellows, and staff surgeons were recruited from the Division of Neurosurgery at the University of Toronto. Each subject was asked to independently perform an ETV on the simulator. Standard neuroendoscopic instruments were used, including a MINOP 0° rigid endoscope, trocar, and grasping and dissecting forceps (Aesculap, Inc.). Irrigation

with normal saline was also provided. Video was captured from the endoscope during the procedures and was stored on a personal computer for editing and analysis.

After the procedure, the surgeons answered a questionnaire regarding the realism (face validity) and teaching effectiveness (content validity) of the simulator. Nine items were included in the questionnaire (Table 1). Items 1–4 evaluated the simulator's face validity, while Items 5–9 evaluated its content validity. Participants were asked to rate their level of agreement with each item by means of a 5-point Likert scale, according to the following de- scriptions: 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree. Participants were also asked to provide open-ended comments regarding the simulator's realism and effectiveness as a training tool.

Table 1. Summary of the questionnaire results ($n = 25$)[a]

Questionnaire Item	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
1. The camera view is comparable to what you would see in a real surgical patient.	0 (0%)	0 (0%)	1 (4%)	14 (61%)	8 (35%)
2. Performing the ventriculostomy on the floor of the third ventricle in the model feels like it does in reality.	0 (0%)	0 (0%)	1 (4%)	16 (64%)	8 (32%)
3. The simulator matches actual tissue properties closely.	0 (0%)	0 (0%)	1 (4%)	19 (76%)	5 (20%)
4. The bleeding looks realistic.	0 (0%)	0 (0%)	0 (0%)	12 (48%)	13 (52%)
5. This model helps to develop the camera skills needed for ETV.	0 (0%)	0 (0%)	0 (0%)	7 (29%)	17 (71%)
6. This model helps to develop the hand-eye coordination needed for ETV.	0 (0%)	0 (0%)	0 (0%)	8 (32%)	17 (68%)
7. The ventriculostomy task is a valuable training exercise.	0 (0%)	0 (0%)	0 (0%)	5 (20%)	20 (80%)
8. Use of this model will increase resident competency when used to train residents prior to their first ETV.	0 (0%)	0 (0%)	0 (0%)	5 (20%)	20 (80%)
9. I would be interested in using this model to train residents.	0 (0%)	0 (0%)	0 (0%)	6 (24%)	19 (76%)

[a] For item 1, $n = 23$ and for item 5, $n = 24$.

Data Analysis

Questionnaire data were analyzed using SPSS Statistics for Windows (version 22, IBM Corp.). The distribu- tion of responses for each questionnaire item was calculated. Questionnaire items that were partially or incorrectly completed were excluded from the analysis. The average overall rating (Items 1–9), average rating of realism (Items 1–4), and average rating of efficacy (Items 5–9) were calculated for each participant. Mean values for each rating were calculated for 3 evaluator groups differentiated by level of experience (PGY 1–2 = novices, PGY 3–6 = senior residents, and fellows and staff = neurosurgeons). A 1-way ANOVA was conducted to deter- mine if differences in ratings between evaluator groups were statistically significant ($p < 0.05$).

Results

We successfully built a low-cost, reusable (and reproducible) silicone-based ETV simulator that realistically mimicked the normal mechanical properties of a 4-month-old child with hydrocephalus (Video: https://www.youtube.com/watch?v=C57wr0b9k-E) .

Realistic intraventricular landmarks including the choroid plexus, veins, mammillary bodies, infundibular re- cess, and basilar artery were successfully created (Figs. 2 and 3). The thinned-out third ventricle floor dissected appropriately and was quickly replaceable. Bleeding scenarios were successfully incorporated. Standard neuroendoscopic equipment including irrigation was used to per- form the ETV. The simulator could be set up in minutes, was easily cleaned, and did not require maintenance or special storage. The production costs were $452 for the molds (fixed costs) and $160.50 for each simulator. The simulator required 55 hours to build, with 10–15 hours of labor. A limited number of models for academic courses can be fabricated on a cost recovery basis (contact corresponding author for details).

Twenty-five neurosurgeons in various stages of their career participated in the second part of the study: 16 residents (PGY 1 [n = 4], PGY 3 [n = 3], PGY 4 [n = 4], PGY 5 [n = 4], and PGY 6 [n = 1]), 5 fellows, and 4 adult and pediatric staff neurosurgeons. The median number of ETVs previously performed by this group was 10 (interquartile range 0–20).

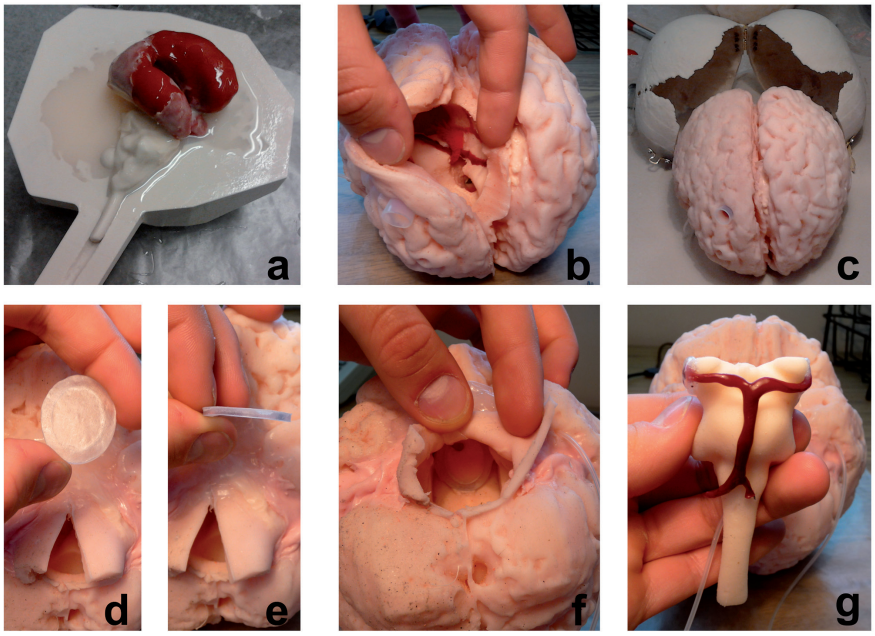

Figure 2. Photographs of the ETV simulator. From top left clockwise: a) Brain, brainstem, ventricle, and prepontine cistern molds cast with silicone, b) Anatomical structures of the right lateral ventricle including septum pellucidum, foramen of Munro, choroid plexus, anterior septal and thalamostriate veins, d) and e) Replaceable third ventricular floor, f) Installed third ventricular floor, g) Brainstem and basilar artery.

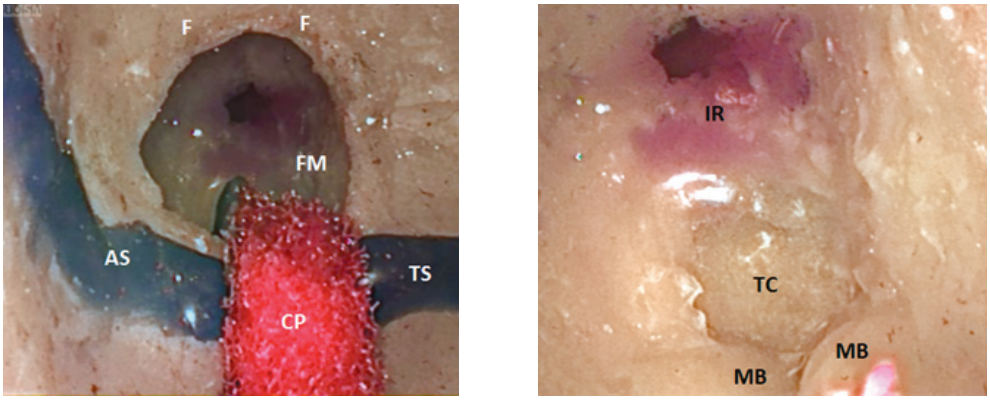

Figure 3. Intraventricular views. Left: Right lateral ventricle. AS = anterior septal vein; CP = choroid plexus; F = fornix; FM = foramen of Monro; TS = thalamostriate vein. Right: Third ventricle. IR = infundibular recess; MB = mammillary bodies; TC = tuber cinereum.

Results of the questionnaire are reported in Table 1. Three participants had incompletely or incorrectly answered a single item on the questionnaire and therefore their responses to these items were omitted from the analysis. More than 95% of participants agreed or strongly agreed that the camera view was comparable to that seen in a real patient and that performing the ventriculostomy in the model felt like it does in reality. Most participants agreed or strongly agreed that the mechanical properties of the simulator closely matched live tissue properties, and all agreed that the bleeding looked realistic. Furthermore, all participants agreed or strongly agreed that the ETV simulator helped develop the camera skills and hand-eye coordination needed for ETV and that it was a valuable training exercise and would increase resident competency prior to performing their first actual ETV. All participants agreed or strongly agreed that they would be interested in using the model to train residents.

There were no statistically significant differences between average overall ratings from the 3 evaluator groups (1-way ANOVA, $p = 0.19$): novices (mean 4.3 ± 0.3 [± SD]), senior residents (mean 4.6 ± 0.3), and neurosurgeons (mean 4.6 ± 0.2). Additionally, no statistically significant differences were found between the average rating on realism (Items 1–4) and efficacy (Items 5–9) for each of the 3 groups ($p = 0.46$ and $p = 0.16$, respectively).

The provided open-ended comments were consistent with the results of the questionnaire; the participants appreciated the ability to use real instruments, the realistic tactile feedback especially when passing through the third ventricular floor, the realistic appearance of bleeding, and the ability to build teamwork. Several suggestions were provided to improve future iterations of the simulator: designing complex third ventricular floors (i.e., thick, opaque, bulging, and with presence of Liliequist's membrane) and modifying the intraventricular anatomy (reducing the size of the foramen of Monro and the size of the mammillary bodies, including the infundibulum, and adjusting the orientation of the veins).

Discussion

Endoscopic third ventriculostomy is an effective and widely accepted treatment for obstructive hydrocephalus but it is technically demanding due to limited

depth perception, narrow ranges of motion, limited tool dexterity, and the presence of critical surrounding anatomy.[4,9,23,29] As a result, it is a challenging but essential procedure to learn during residency. To learn, practice, and perfect the skills required for ETV, exposure to a large volume of cases is needed. Several factors have contributed toward this trend of declining case volumes, including work hour limits, changes in disease management, rapidly advancing technology, subspecialization, and increased demand for patient safety and cost-efficient health care practices.[11,20,21] As a result, there has been an increased interest in the use of simulation to train residents in a risk-free environment without time or resource constraints.[22,26] Simulators have been shown to improve real-life surgical performance and accelerate learning curves, resulting in improved patient outcomes, fewer complications, and decreased operative times.[16,28,31]

Currently available ETV simulators include virtual reality systems (NeuroTouch)[3,6,25] and synthetic phantoms (S.I.M.O.N.T. Neurosurgical Endotrainer [Sinus Model Oto-Rhino Neuro Trainer, Pro Delphus Co.]).[7,12,18] A key advantage of NeuroTouch is its ability to provide real-time feedback on important performance metrics such as tool trajectories, contact forces with critical structures, procedure time, and ventriculostomy location.[3] However, high cost, inaccessibility, the lack of a sufficiently accurate haptic interface, and unrealistic dissection of the third ventricular floor are its biggest obstacles.[25] The S.I.M.O.N.T. synthetic simulator has been shown to be highly realistic and improve surgical performance, with a 42% reduction in trainee errors after use of the simulator.[7] However, a key drawback is that the model is not patient specific and therefore it does not allow preoperative rehearsal of actual patient cases. In addition, the brain and ventricular system needs to be replaced after each use, leading to increased costs.

To our knowledge, the presented simulator is the first patient-specific synthetic simulator developed for neurosurgery. Several key advantages were demonstrated during the evaluation process, including its low cost, robustness, quick setup time, portability, reusability, and lack of special maintenance or storage requirements. Printing the brain and ventricular system of other patients would follow the same process, and, with the advancement of 3D printing technology, could potentially be automated. Results of the questionnaire established the simulator's face and

content validity. More than 95% of participants agreed that the simulator's anatomical features and tissue properties were realistic representations of those experienced during an ETV. All participants agreed that the simulator helped develop the hand-eye coordination, instrument handling, and camera skills required for ETV; that it was a valuable training exercise; and that it provided realistic bleeding scenarios.

During the evaluation process, some limitations of the simulator became clear. First, it was not possible for the participants to plan the ideal location of the skin incision and bur hole based on preoperative MRI. Second, participants were unable to practice making the skin incision, drill the bur hole, or perform the corticotomy. Third, the model was not integrated with image guidance (either ultrasound or neuronavigation) to help guide trocar insertion into the ventricle. Fourth, participants were not able to use bipolar cautery to achieve hemostasis, relying only on irrigation. Fifth, the third ventricle floor was not patient specific. For example, certain features such as floor thickness, (downward) bulging of the floor, distance between the mammillary bodies and infundibular recess, presence of Liliequist's membrane, and the exact relationship of the basilar artery to the floor could not be specifically designed. Sixth, it was not possible to observe pulsations of the edges of the ventriculostomy site to ensure the stoma was adequate. Seventh, it was not possible to practice closure of the incision. Lastly, we were unable to track instrument motions or applied tool-tip forces to evaluate surgeon performance. These limitations will be addressed in future iterations of the simulator design.

There were some limitations in the design of the evaluation study. First, some participants, in particular the PGY 1 residents, had little or no previous experience performing an ETV, thereby limiting their ability to accurately evaluate the simulator's realism and teaching effectiveness. Second, the subjective and retrospective nature of comparisons between the simulator and real-life cases may have introduced recall bias. Lastly, there were a limited number of participants, all from the University of Toronto, affecting the generalizability of the results.

Conclusions

We have successfully created a low-cost, reusable, patient-specific silicone-based ETV simulator that has high face and content validity. This simulator may help residents to increase their familiarity with the camera skills, instrument handling, and hand-eye coordination required to successfully perform an ETV. The development of future iterations will focus on integration with image guidance systems, incorporation of presurgical planning, design of patient-specific intraventricular landmarks, and providing real-time performance feedback. In addition, models for other age groups and intraventricular pathologies such as tumors or colloid cysts will be developed. Once these models have been fully developed, large prospective randomized trials involving novice and expert surgeons will be required to evaluate the simulator's face, content, and construct validity. Furthermore, comparisons against other training models such as virtual reality simulation will be required.

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