Development and validation of a high-fidelity surgical simulator for endoscopic colloid cyst resection

Vivek P. Bodani, MD, PhD (Cand) (SSTP)[1, 2, 3], Gerben E. Breimer, MD, PhD[1], Faizal A. Haji, MD, PhD[4], James M. Drake, MB, BCh, MSc, FRCSC[1, 2, 3]

[1]Center for Image Guided Innovation and Therapeutic Intervention, The Hospital for Sick Children
[2]Division of Neurosurgery, Department of Surgery, University of Toronto
[3]Institute of Biomaterials and Biomedical Engineering, University of Toronto
[4]Division of Clinical Neurological Sciences, Western University

Author Contributions

Study conception: Bodani, Breimer, Drake. Simulator development: Bodani, Breimer. Feedback survey development: Bodani, Haji. Acquisition of data: Bodani. Statistical analysis and interpretation of data: Bodani. Drafting the article: Bodani. Critically revising the article: all authors. Study supervision: Drake.

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Introduction

Colloid cysts of the third ventricle account for 0.5–2% of all intracranial tumors[1]. Endoscopic resection of these lesions has gained increased popularity because of its reduced morbidity compared to open microsurgical techniques[2]. However, this approach is technically challenging due to the limited access to and visualization of the cyst's attachment to the roof of the third ventricle. As a result, significant debate remains over the effectiveness of the endoscopic approach, with concerns raised over the rates of gross total resection, cyst recurrence, and the need for reoperation[2]. Because of these challenges, it is critical that neurosurgeons gain extensive experience with this approach during their surgical training. However, the ability for trainees to gain the required level of experience has become increasingly limited due to increased work hour restrictions, increased sub-specialization, rapidly advancing technology, and increased demands for patient safety and cost-efficient healthcare practices[3–6]. Simulation-based surgical education may provide trainees with a risk-free environment to learn and practice procedures without time or resource constraints[7–9]. They have been shown to improve surgical performance and accelerate learning curves, resulting in improved patient outcomes, fewer complications, and decreased operative times[10–12]. The purpose of this study was to develop a realistic, low-cost, reusable, and patient-specific synthetic simulator for endoscopic colloid cyst resection and evaluate its realism (face validity) and utility as a training instrument (content validity).

Methods

The preoperative neuroimaging of a patient with hydrocephalus and a third ventricle colloid cyst was segmented using image processing software to produce virtual models of the skull, brain, ventricles, and colloid cyst (Figure 1). These structures were produced using rapid prototyping (3D printing) and silicone molding techniques (Figure 2A–2F). The mechanical properties of the silicone were adjusted to closely resemble brain tissue. The brain was encased in the skull and fully submerged in a water bath to simulate the cerebrospinal fluid. The choroid plexus and intraventricular veins were added to the lateral and third ventricles. A replaceable colloid cyst was secured to the roof of the third ventricle. The cyst was filled with a viscous fluid to simulate the cyst contents and had a thin cyst wall that dissected appropriately.

The simulator was incorporated into a neuroendoscopy training workshop composed of didactic lectures and practical exercises. Neurosurgical residents and fellows performed a simulated endoscopic colloid cyst resection using a 30°-angled rod-lens endoscope and bimanual neuroendoscopic system (MINOP InVent, Aesculap, Inc., Center Valley, PA, USA) via a right frontal burr hole (Figure 2G–2L). An electromagnetic neuronavigation system (StealthStation EM, Medtronic, Inc., Minnesota, MN, USA) was used for image-guidance. Participants worked in pairs, one acting as the primary surgeon directing the operation and maneuvering the endoscopic instruments, and the other acting as an assistant to position the camera as directed by the primary surgeon. All participants had the opportunity to act as both the primary surgeon and the assistant. A neurosurgical expert in neuroendoscopy and colloid cyst resection provided specific and immediate feedback throughout the procedure. After identifying the relevant intraventricular anatomy (foramen of Munro, colloid cyst, anterior septal and thalamostriate veins, choroid plexus), participants fenestrated the cyst wall using endoscopic scissors. A clear 6-French nasogastric tube with the distal side ports trimmed off was used to aspirate the cyst contents. Endoscopic grasping forceps were used to grasp the cyst wall and dissect it from the roof of the third ventricle using a rotary motion of the forceps. The cyst wall was removed from the ventricles along with the endoscope and trocar via the endoscopic tract. A final inspection of the ventricles was performed to rule out a remnant cyst wall and floating cyst debris, particularly near the cerebral aqueduct.

Participants were asked to evaluate the simulator using a 15-item questionnaire in order to establish its face and content validity. Fourteen questions were rated using 5-point Likert scales with the following anchor points: 1 – strongly disagree, 2 – disagree, 3 – neutral, 4 – agree, and 5 – strongly agree. These questions were used to evaluate 4 main categories: simulator realism, instrument handling, procedural content, and overall task fidelity. One additional question, requiring a "yes" or "no" response, asked participants if they would use the simulator for personal training, or the training of residents/fellows in their program, in endoscopic colloid cyst resection. Staff neurosurgeons with expertise in intraventricular neuroendoscopy and colloid cyst resection were asked to provide open-ended comments on the simulator's realism and teaching content and recommendations for improving the design of future iterations of the simulator.

Results

Fourteen trainees were enrolled in the validation study (6 junior residents (PGY 1–3) [42.9%], 4 senior residents (PGY 4–6) [28.6%], and 4 fellows [28.6%]). The median number of microsurgical or endoscopic colloid cyst resections observed, assisted in, or performed as the primary surgeon was 2.5 (interquartile range: 0–5). The results of the questionnaire are summarized in Table 1. Participants found the simulator to be highly realistic (mean [SD] 4.39 [0.63]) and especially appreciated to use of actual neuroendoscopic instruments (mean [SD] 4.51 [0.59]). The procedural content was also rated highly (mean [SD] 4.24 [0.85]), however the overall task fidelity was rated slightly lower (mean [SD]: 3.98 [0.65]). Thirteen participants (92.9%) indicated that they would use the simulator for additional training. Two staff pediatric neurosurgeons with expertise in intraventricular neuroendoscopy and colloid cyst resection (one from the University of Toronto and one from NewYork-Presbyterian/Weill Cornell Medical Center) provided recommendations to improve the simulator's design. Recommendations were made to: 1) increase the case complexity for experienced trainees (i.e. small ventricles, choroid plexus adherent to cyst wall, increased cyst fluid viscosity, firm attachment of cyst to roof of third ventricle, intraseptal cyst location, bleeding scenarios due to choroid plexus or internal cerebral vein injury), and 2) incorporate additional instrumentation (i.e. electrocautery, ultrasound, tissue shavers).

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Discussion

The apprenticeship training model has served as a cornerstone of surgical education[13]. However, this model has come under increased scrutiny in an era of decreasing operative exposure during residency[5], both in terms of the number and diversity of cases performed and the increasingly limited role played by trainees during these procedures. The ethical and medicolegal concerns of allowing trainees to practice on actual patients and the increasing demands for reduced healthcare spending and wait-times have contributed to this trend. Increased subspecialization, rapid technological advancement, and resident work hour restrictions have also played a significant role[3–6]. The establishment of educational milestones and shift towards a competency-based training curriculum may present a solution to these challenges. To facilitate these efforts, there is a need for validated surgical simulators that allow trainees to engage in deliberate practice of surgical skills in a stress-free environment without any risk to patients[7–9]. Neuroendoscopic procedures are an ideal procedure for simulation training as they are technically challenging (limited instrument dexterity, limited field of view and depth perception, constrained workspace) and carry the risk for significant morbidity and mortality[14]. Endoscopic colloid cyst resection, in particular, is associated with a steep learning curve and requires extensive training and experience with bimanual intraventricular neuroendoscopic techniques and specialized equipment (neuronavigation, tissue shaving devices) in order to achieve good outcomes[2,15–17].

Current neuroendoscopic simulators include virtual reality systems (NeuroTouch)[18] and synthetic models (S.I.M.O.N.T. Neurosurgical Endotrainer)[19–20]. NeuroTouch is reusable and provides accurate, real-time feedback of resident performance[18] However, high cost, inaccessibility, the lack of an accurate haptic interface and the inability to use actual surgical instruments are its biggest obstacles[7,18]. In addition, intraventricular pathology like tumors and cysts have yet to be incorporated. S.I.M.O.N.T. is a realistic, single-use synthetic simulator that has been shown to improve surgical performance and reduce errors[19]. However, the model is expensive (US$6367.50)[20] and lacks patient-/procedure-specificity, and therefore does not allow preoperative rehearsal of actual patient cases.

We have designed a high-fidelity surgical simulator for endoscopic colloid cyst resection that incorporates actual neuroendoscopic instruments and neuronavigation. The simulator allowed trainees to foster technical and non-technical skills (i.e. leadership, teamwork, communication, and decision making) under the direct supervision of an expert neurosurgeon providing specific and immediate performance feedback. To the best of our knowledge, this is the first procedure- and patient-specific synthetic simulator for endoscopic colloid cyst resection. It is also one of the most cost-effective neuroendoscopy simulators currently available (fixed costs: $727.61, variable costs: $486.53) and can be fabricated relatively easily (production time: 66 hours, labor: 8 hours). The simulator has an unlimited shelf life with no special maintenance or storage requirements. Another key advantage of the simulator is its reusability. The only disposable component is the colloid cyst which is inexpensive, easy to fabricate, and quickly replaceable.

There are several limitations with the design and implementation of the simulator. First, the overall task fidelity received the lowest rating of the 4 main categories (mean [SD] 3.98 [0.65]). The main reason for this was the inability of participants to suspend disbelief (i.e. participants did not feel they were operating on an actual patient). Second, the simulator received a low score on its degree of difficulty (mean [SD] 3.71 [1.07]). Subgroup analysis by training level revealed non-significant differences in opinion on the degree of difficulty of the simulator, with junior residents finding the simulator to be more technically challenging than senior residents and fellows (mean [SD], junior residents: 4.17 [0.75], senior residents: 3.50 [1.73], fellows: 3.25 [0.50], p-value 0.40). Lastly, the high cost and relative inaccessibility of neuro-endoscopic instruments and neuronavigation systems for the sole purpose of training is a significant limiting factor. To date, the use of our simulator has been restricted to prescheduled, limited duration (typically 1 day) practical courses typically held at a surgical skills center and using training systems provided by industry. Establishing this infrastructure, or finding low-cost alternatives, will be a key requirement for incorporating a neuroendoscopy simulation program into the training curriculum, in particular one that will allow trainees to practice procedures in a deliberate and repeated fashion.

The validation study had several limitations. Participants were asked to compare the simulated procedure to previous "real-world" encounters with the procedure. This may have introduced a recall bias to the results. In addition, the majority of participants were relatively inexperienced with endoscopic colloid cyst resection, limiting their ability to accurately evaluate the simulator's realism and teaching content. Lastly, the size of the study population was small, limiting the statistical power and generalizability of the results.

Conclusion

We have successfully developed a patient-specific, silicone-based simulator for training residents in endoscopic colloid cyst resection. In addition, we have provided an initial validation of the simulator's realism, procedural content, and value as an educational tool. Future work will focus on increasing the overall task fidelity, increasing the case complexity, and incorporating additional instrumentation. Most importantly, the development of objective expert-rated performance assessment tools and the conduction of large-scale prospective validation studies will be necessary to evaluate the transfer of skills from the simulation environment to the operating room and to determine the impact of simulator practice on surgeon preparedness, complication reduction, and operating room efficiency.

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Figures and Tables

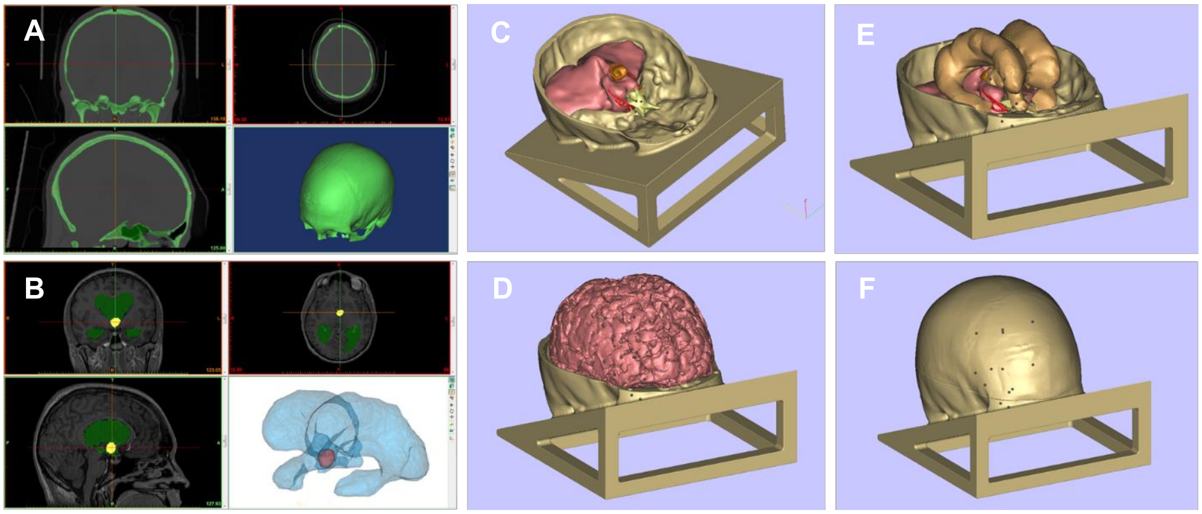

Figure 1. Segmentation of pre-operative patient images and 3D modeling. A) skull segmentation using non-contrast CT. B) colloid cyst and ventricle segmentation using T1-weighted gadolinium-enhanced MRI. C) 3D model of skull base, cerebellum, and brainstem. D) 3D model of cerebral hemispheres. E) 3D model of ventricles. F) 3D model of skull and skull base.

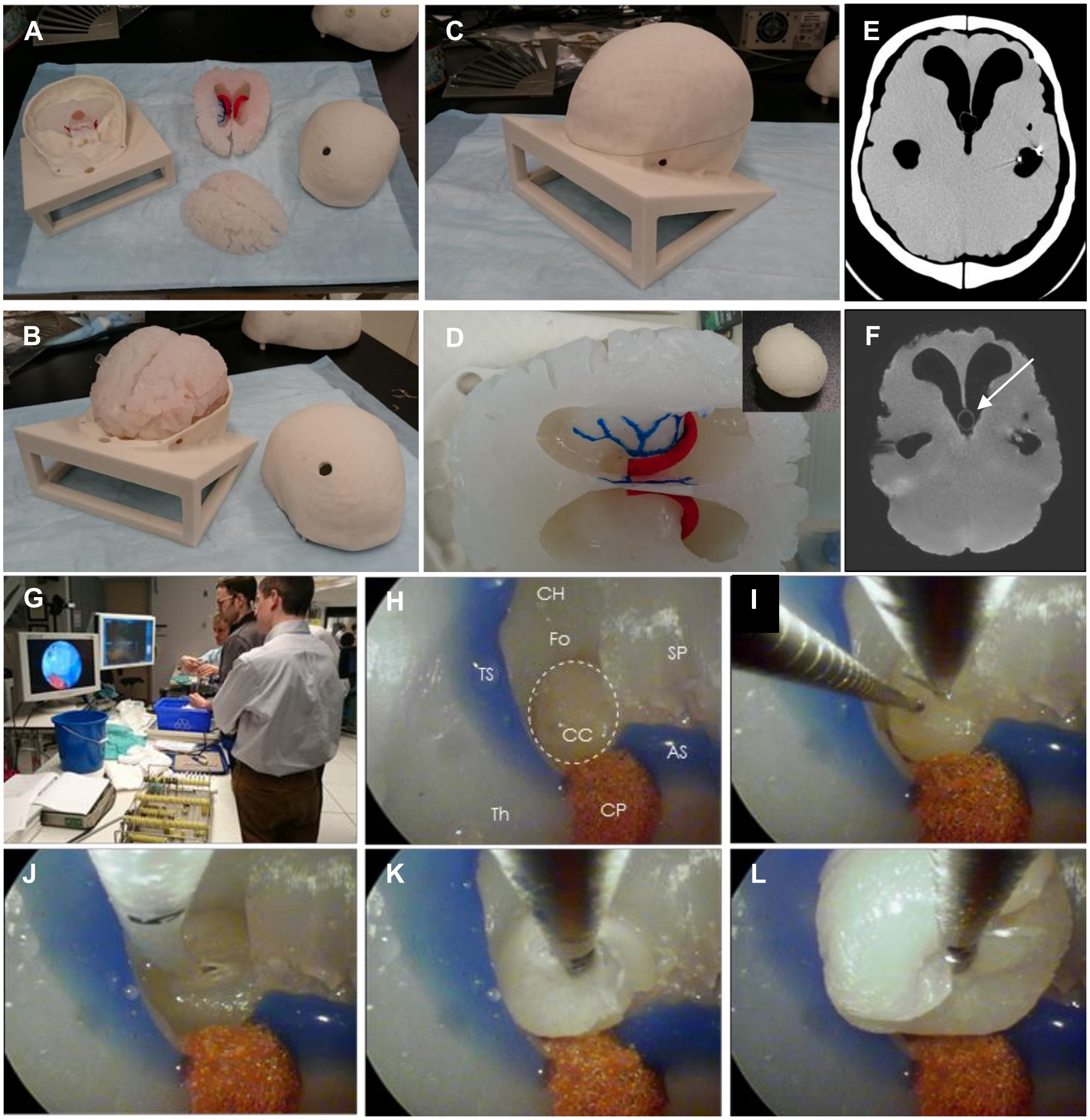

Figure 2. Endoscopic colloid cyst simulator. A) disassembled simulator showing the skull base, brain, and skull. B) simulator with skull cap removed. C) assembled simulator. D) lateral ventricles and intraventricular anatomy including septal and thalamostriate veins, choroid plexus, and colloid cyst (*inset*). E) axial CT of simulator. F) axial T1-weighted MRI of simulator (colloid cyst indicated by arrow). G) procedure setup and instrumentation (rigid endoscope, bimanual instrumentation, neuronavigation). H) left lateral ventricle demonstrating anterior septal (AS) and thalamostriate veins (TS), choroid plexus (CP), thalamus (Th), caudate head (CH), fornix (Fo), septum pellucidum (SP), colloid cyst (CC), and foramen of Monro (*dashed circle*). I) fenestrating cyst wall with scissors. J) aspirating cyst contents with a 6-French nasogastric tube. K) dissecting cyst wall from the roof of the third ventricle using a rotary motion of the endoscopic forceps. L) extirpating the cyst wall from the ventricles.

Table 1. Feedback Survey Results

Survey Item	**Rating (mean [SD])**
Anatomy	***4.39 [0.63]***
The **surface anatomy** was realistic and appropriately detailed for choosing an entry point/trajectory to insert the endoscope	4.46 [0.66][1]
The size and shape of the **ventricles** and the **intra-ventricular anatomy** (veins, choroid plexus, foramen of Munro, fornix) was realistic and had the appropriate detail required for navigation to the colloid cyst	4.36 [0.63]
The **colloid cyst** was realistic and had the appropriate detail required to perform the resection (size, location, appearance of cyst wall, appearance of cyst fluid)	4.36 [0.63]
Instrument Handling	***4.51 [0.59]***
The handling of the **endoscope** was realistic	4.71 [0.47]
The handling of the **endoscopic tools** was realistic	4.71 [0.47]
The **haptic (tactile) feedback** from the simulator was realistic (thickness and tactile properties of cyst wall, viscosity of cyst fluid)	4.36 [0.63]
The **response of the tissue to manipulation** by the endoscope/endoscopic tools was realistic (i.e. cutting the cyst wall, aspirating fluid contents, extirpating cyst wall from ventricles)	4.29 [0.61]
Use of the **neuronavigation** system was realistic	4.45 [0.69][2]
Content of Procedure	***4.24 [0.85]***
The **steps** required to complete the task were representative of the steps required to complete the real procedure	4.43 [0.65]
The **skills** required to complete the task were representative of the skills required to complete the real procedure	4.57 [0.51]
This task was **technically challenging** for me	3.71 [1.07]
Overall Task Fidelity (Realism)	***3.98 [0.65]***
The simulation **suspended disbelief**	3.71 [0.61]
The **simulator environment** is realistic of the real-life situation (e.g. look and feel of the endoscope and tool handles, position of the patient head, position of the rest of the equipment, look and feel compared to a real OR, etc.)	4.20 [0.58]
Real life factors, situations and variables were built into the simulation scenario	4.00 [0.68]
Would you use this simulator for your personal training, or the training of residents/fellows in your program, on endoscopic colloid cyst resection?	***n (%)***
Yes	13 (92.9)
No	0 (0)
Unanswered	1 (7.1)

[1]One participant did not rate this item and was excluded from the analysis.
[2]Three participants did not rate this item and were excluded from the analysis.