The Development of a Virtual Simulator for Training Neurosurgeons to Perform and Perfect Endoscopic Endonasal Transsphenoidal Surgery

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BACKGROUND: A virtual reality (VR) neurosurgical simulator with haptic feedback may provide the best model for training and perfecting surgical techniques for transsphenoidal approaches to the sella turcica and cranial base. Currently there are 2 commercially available simulators: NeuroTouch (Cranio and Endo) developed by the National Research Council of Canada in collaboration with surgeons at teaching hospitals in Canada, and the Immersive Touch. Work in progress on other simulators at additional institutions is currently unpublished.

OBJECTIVE: This article describes a newly developed application of the NeuroTouch simulator that facilitates the performance and assessment of technical skills for endoscopic endonasal transsphenoidal surgical procedures as well as plans for collecting metrics during its early use.

METHODS: The main components of the NeuroTouch-Endo VR neurosurgical simulator are a stereovision system, bimanual haptic tool manipulators, and high-end computers. The software engine continues to evolve, allowing additional surgical tasks to be performed in the VR environment. Device utility for efficient practice and performance metrics continue to be developed by its originators in collaboration with neurosurgeons at several teaching hospitals in the United States. Training tasks are being developed for teaching 1- and 2-nostril endonasal transsphenoidal approaches. Practice sessions benefit from anatomic labeling of normal structures along the surgical approach and inclusion (for avoidance) of critical structures, such as the internal carotid arteries and optic nerves.

CONCLUSION: The simulation software for NeuroTouch-Endo VR simulation of transsphenoidal surgery provides an opportunity for beta testing, validation, and evaluation of performance metrics for use in neurosurgical residency training.

KEY WORDS: Computer simulation, Endoscopy, Neurosurgery, Training, Transsphenoidal, Virtual reality

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There is increasing support for the concept that surgical skills should be initially learned in a laboratory setting rather than in the operating room.[1-15] Cost-effective alternatives to traditional training schema have been advocated.[16-18] Public demand and the highly visible safety programs in the aviation industry have led to new educational paradigms in neurosurgery and other surgical specialties.[19-23] This is particularly true in teaching the commonly performed endoscopic endonasal transsphenoidal surgical approach.[24-28] The indirect view and confined work space characteristic of this procedure increase the potential for technical errors.

ABBREVIATIONS: CTA, cognitive task analysis; **VR,** virtual reality

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Safe performance of this approach relies on pliable and easily manipulated soft tissues, a condition that is difficult or impossible to simulate with embalmed surgical specimens.[29,30] Three-dimensional computer-based models have been described to augment surgical education and provide an opportunity for preoperative rehearsal of transsphenoidal procedures.[31-34] An additional advantage of virtual reality (VR) over cadaver training will be its potential to study an individual patient's endoscopic anatomy before the actual surgery.[34-43] Simulation with haptic feedback could further answer some of these educational needs.[3,4,44] Some of the first developments in VR endoscopy were for otolaryngologists, for the demanding training needs of endoscopic sinus surgery.[35,45,46] Experience with validation studies in general surgery showed that the use of virtual laparoscopy simulators increased accuracy, reduced errors, and decreased the time to complete a task. The National Research Council Canada has described a first attempt to develop standardized training modules for technical skills acquisition in neurosurgical oncology for use on the National Research Council Canada NeuroTouch VR simulator (Figure 1).[47] Work is currently under way to evaluate technical expertise in neurosurgery in the VR environment.[48-52] Indeed, international neurosurgery educators have recently expressed the opinion that "VR-based simulators in general are now matured enough to consider them for a worldwide regular surgery curriculum" (Cakmak response in Delorme et al article[17]).

Objective

The objective of this report is to describe the development of 1 simulator that facilitates the acquisition and assessment of technical skills for endoscopic endonasal transsphenoidal procedures. The goal is to create and define a program for resident training that may be applied in residency curricula and at international neurosurgical residency boot camps. The simulation should begin with sessions that familiarize the user with the pertinent visible and nearby anatomy and appropriate use of visualization devices and surgical instruments. The tasks should become increasingly difficult and complex. Finally, they should provide the users with feedback, both positive and negative, on their performance of VR surgery.

PATIENTS AND METHODS

Identification of Core Technical Skills

In previous work in developing the fundamentals of neurosurgery as standardized training modules for neurosurgery technical skills training, our group began by identifying the skills that a resident is required to master to graduate in neurosurgery.[47] We consulted Canadian and American curricula, focused on neurosurgical oncology, and prioritized performance objectives that involved hands-on techniques. The identified skills were grouped into broad categories. Of these, those that are pertinent to the current work for endoscopic endonasal transsphenoidal procedures are highlighted in bold in Table 1.

Previous work by Bakker et al,[53] in which they investigated the training needs for functional endoscopic sinus surgery, was also consulted. This group had outlined and classified 18 skill requirements in order of difficulty for functional endoscopic sinus surgery, based on the results of questionnaires distributed to 32 otolaryngologists. Overall, the authors found skills that required manual dexterity to be less difficult, whereas skills related to spatial orientation were judged to be the more difficult skills to master.

FIGURE 1. *NeuroTouch, the National Research Council Canada's virtual reality simulator. The system was designed for neurosurgical resident training with exercises ranging from basic instrument handling of commonly used instruments to realistic neuro-oncology procedures for both open cranial and endoscopic interventions. The simulator in endonasal configuration is shown.*

Our previous work required definition of appropriate training exercises that could serve to teach the relevant skill set. This was accomplished by performing a cognitive task analysis (CTA) for the endoscopic resection of a pituitary adenoma. A CTA involves breaking down a given procedure into its elemental subtasks, including surgical cues and decision loops, to reveal simplified tasks that could be suitable as training exercises.[23,38,51]

Specifications for Endoscopic Endonasal Transsphenoidal Simulation Training

Endoscope

The simulator graphics mimic the screen visualization of a typical rigid rod-lens endoscope with a 4-mm outer diameter, with the associated need

TABLE 1. Technical Skill Requirements for Graduation in Neurosurgical Oncology With Emphasis of Skills Specific to Endoscopic Endonasal Transsphenoidal Procedures[a]

1	Open and close scalp incisions
2	Perform ventriculostomies, place lumbar drains and intracranial monitors
3	Position patients for craniotomy
4	Perform the opening and closing of craniotomies
5	Resect cranial lesions
6	Perform image-guided biopsies
7	Demonstrate facility with the use of surgical instruments including operating the microscope and endoscope
8	Identify interface between the tumor and brain and use as an operating plane for tumor resection
9	Identify anatomic landmarks, functional regions, and major structures
10	Show how to minimize and control intraoperative bleeding
11	Perform resection of extra-axial and intra-axial brain tumors
12	Perform resection of supra- and infratentorial brain tumors
13	Perform resection of pituitary lesions
14	Perform basic cranial base procedures
15	Detect and handle unexpected complications

[a]Adapted from Choudhury et al.[47]

to direct and cleanse it in such a way as to maintain visualization of the surgical corridor.

Neurosurgical Tools

The simulator allows manipulation of the tools and instruments commonly used during endonasal transsphenoidal surgery, including drills, debrider, suction, cautery, curettes, and forceps. The development of realistic tools that will allow simultaneous use of both hands and will mimic the handling characteristics of commonly used transsphenoidal instruments is undergoing constant refinement.

Anatomy and Tissues

The ideal simulator for transsphenoidal surgery should incorporate tissues that are soft, semisoft, and rigid, as is the case with the variety of real tissues encountered when performing this approach. The debrider and drill have different weights and handling characteristics. Tumors may be soft or firm; they may be variably able to be aspirated or require piecemeal or en bloc mechanical removal. Progressive adoption of extensions to the transsphenoidal approach, with removal of bone along the tuberculum sellae and the planum sphenoidale, creates a need for laboratory practice environments even for the mature neurosurgeon.

Fluids

Fluids, such as blood and cerebrospinal fluid, are encountered when anatomically appropriate, and interface in a realistic manner with the other instruments such as an endoscope, suction, and bipolar cautery.

Development of Endoscopic Endonasal Transsphenoidal Simulation Training Module

Once potential training exercises have been identified, an appropriate pedagogical training module is obtained by expanding the identified manual tasks to include specific learning objectives, levels of difficulty, and performance metrics. The exercises are designed with incremental difficulty, such that successive skills are mastered sequentially rather than all at once. This organization favors optimal learning.[41] Performance metrics are integrated to provide immediate feedback to the user to permit autonomous learning. For completeness, metrics include both measures of efficiency and error. In neurosurgical oncology, the appropriate measures relate to maximizing removal of the lesion while minimizing permanent damage to critical structures. Metrics also calculate blood loss and the duration of the surgery.

The exercises identified from the CTAs are then further detailed through expert interviews to determine which features to include in the tasks to maximize the educational value. This is achieved through questionnaires, discussions, and interviews with subject matter experts. The analyses serve to (1) classify features as essential or optional, (2) set the levels of difficulty, (3) define appropriate performance metrics, and (4) prioritize the features to be developed in simulation. Iterative validation is required as the training modules are refined to ensure that the content remains useful and pertinent.

Training Tasks Identification

Endoscopic skills training can be quite complex due to the unfamiliar anatomy and ergonomics involved. As such, we decided to begin with simple tasks to favor optimal learning of these skills. We focused on manual skills training; specifically, we focused on navigating the surgical instruments through the narrow confines of the nasal cavities. The goal was to organize the tasks such that once the user becomes familiar with a given surgical instrument, the next step is to proceed to practicing technique and, finally, to perform procedures.

The CTA performed for the endoscopic resection of a pituitary adenoma consisted of different phases (preparation, approach, tumor exposure and removal, and closure). Due to the large number of steps and level of detail involved, only the approach phase is described here (Figure 2). The approach was broken down into the nasal, sphenoid, and sellar portions that were further reduced to each elemental subtask. This final breakdown identified the sequence of basic steps to follow to accomplish a particular portion of the procedure. The CTA also proved to be useful by revealing the subtasks: locating the sphenoid ostia and enlarging ostia to reach the sella as suitable training tasks to practice technique. These tasks were selected due to the manual skills and the decision making involved.

Endoscopic Endonasal Transsphenoidal Simulation Features

Endoscope

At present, a VR endoscope with a 4-mm outer diameter with viewing angle of 0° is available, with 30° and 45° lens views and tool simulations under development (Figure 3). The instrument handle replicates a camera, permitting the user to practice holding an endoscope as in the operating room. The endoscope tissue-tool interaction model features an endoscopic view complete with "barrel effect" and lens blurring; the latter occurs when the endoscope tip comes into contact with tissue. The lens can be rinsed clean when a foot pedal is pushed (Figure 1).

Neurosurgical Tools

At present, interchangeable microdebrider and microdrill instrument handles, along with specific tissue-tool interaction models, have been

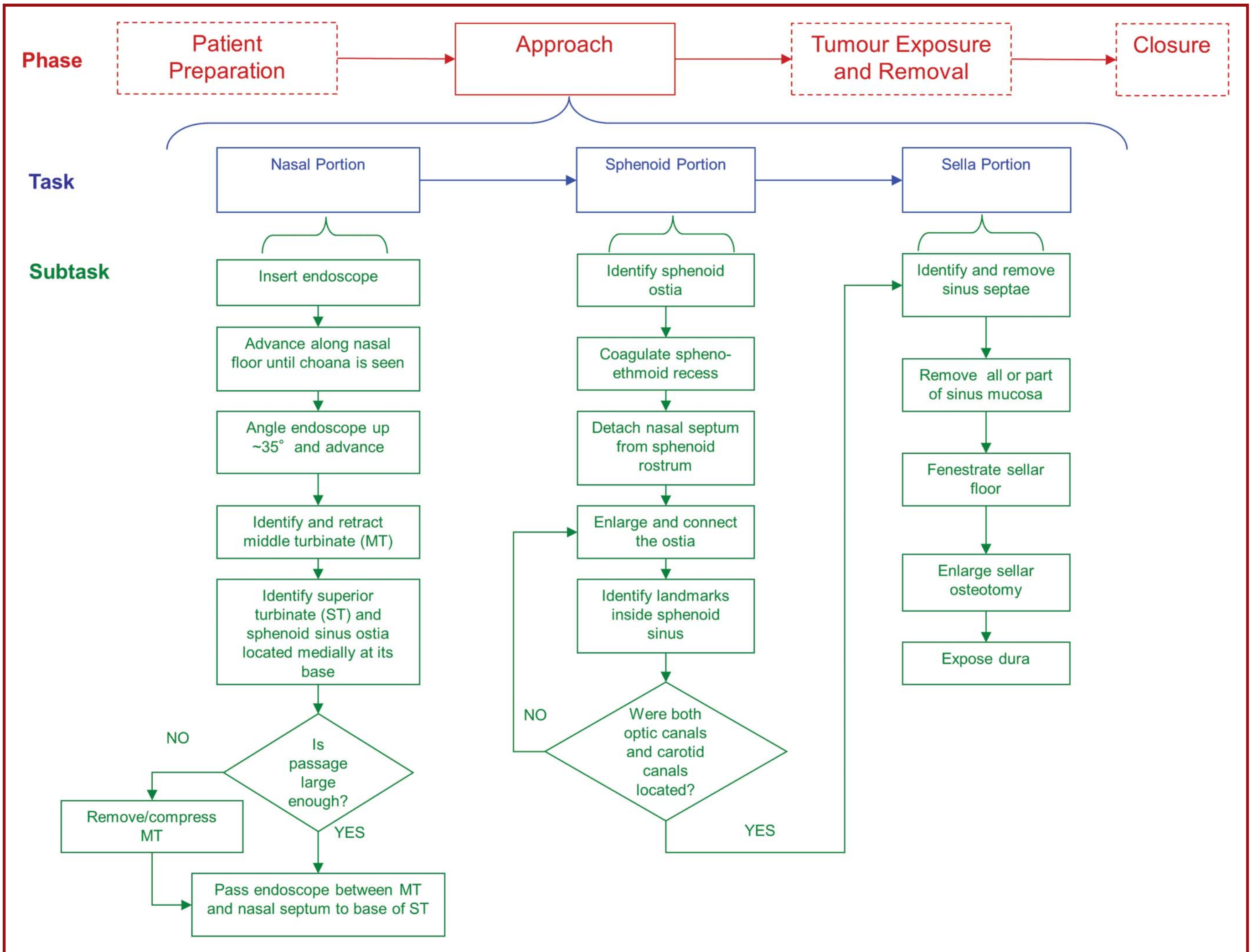

FIGURE 2. *Cognitive task analysis deconstructing the approach phase in the resection of a pituitary adenoma. In this example, locating the sphenoid ostia and reaching the sella were selected as possible training tasks. These subtasks were further broken down to expose features and cues that were potentially important to simulate for training (not detailed here).*

developed for simulation in NeuroTouch (Figures 4 and 5). The microdebrider is simulated as a standard instrument with a 3.5-mm outer diameter and a double serrated tip rotating at 5000 rpm. This instrument is under constant low vacuum to aspirate soft tissue through its side opening. The microdrill is modeled as a typical instrument with a 4-mm outer diameter with a spherical drill burr. The drilling/tip rotation action of both instruments is activated via a foot pedal, and the resulting vibration is felt in the user's hand.

Anatomy and Tissues

The training task of locating the sphenoid ostium involves the nasal phase of the endoscopic removal of pituitary adenomas. It is typically the first major step in the endoscopic transnasal approach to resecting a pituitary adenoma. Using anatomic landmarks, such as the turbinates, choana, and sphenoethmoid recess, the ostium of the sphenoid sinus is located and visualized (see **Video**, **Supplemental Digital Content 1**, which demonstrates labeled normal anatomy encountered during the approach to the sella, http://www.youtube.com/watch?v=s2wGGkpQEXs). The second training task, to enlarge the ostia, is the step required to access the sphenoid sinus during the approach. This task involves drilling through bone to enlarge an already existing opening. Although fluid simulation is important, it is currently not available in NeuroTouch.

Endoscopic Endonasal Transsphenoidal Simulation Training Modules

The selected training tasks were elaborated in complete training modules with the inclusion of learning objectives, target audience, training goals, and customized metrics to assess performance. The tasks were ordered by level of difficulty: (1) endonasal navigation to locate the

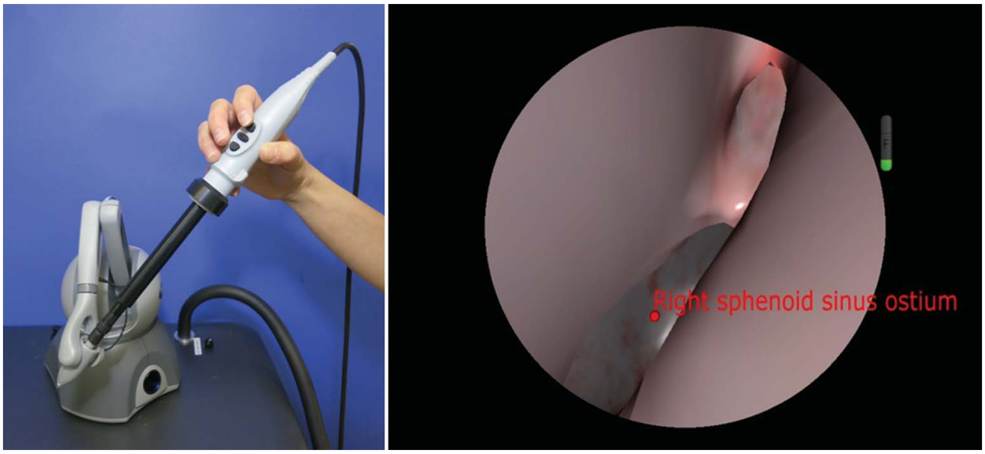

FIGURE 3. *The endoscope model in NeuroTouch is equipped with a physical handle resembling a camera, with a virtual model complete with the endoscopic view.*

sphenoid ostium (navigation only) and (2) endonasal drilling to enter sphenoid sinus (requires navigation + drilling). Currently, the task is being developed to make 2 training approaches available.

A given task itself was structured to include levels of difficulty, related to different patient anatomy. For example, the presence of a septal deviation or small nasal passages makes the landmarks harder to locate and navigation more difficult. Metrics included positive performance measures as well as errors. Complications that can occur include bleeding resulting from tools rubbing on the nasal mucosa or perforating the septum and damage caused by applying force to structures that should normally not be touched, such as the ethmoid sinuses. The complete training module for each task is described, respectively, in Tables 2 and 3.

The goal of the endonasal navigation exercise is to locate and identify the sphenoid ostium. With input from the subject matter experts, it was decided that the pertinent errors include improper tool handling (such as losing orientation or losing sight of the surgical instrument) or using too much force. Performance is optimal when the ostium is located with efficient handling of the endoscope without error. Reasonable time estimates were discussed to be approximately 5 minutes to find the ostium. The simulation automatically captures a successful outcome if the user is able to locate the ostium (target) and hold it in the center of the virtual endoscopic view.

The goal of endonasal drilling is to use the microdrill to enlarge the sphenoid ostia, then to enter the sellar floor with 2 training approaches available. The 1-nostril approach uses the same nare for both the endoscope and the working

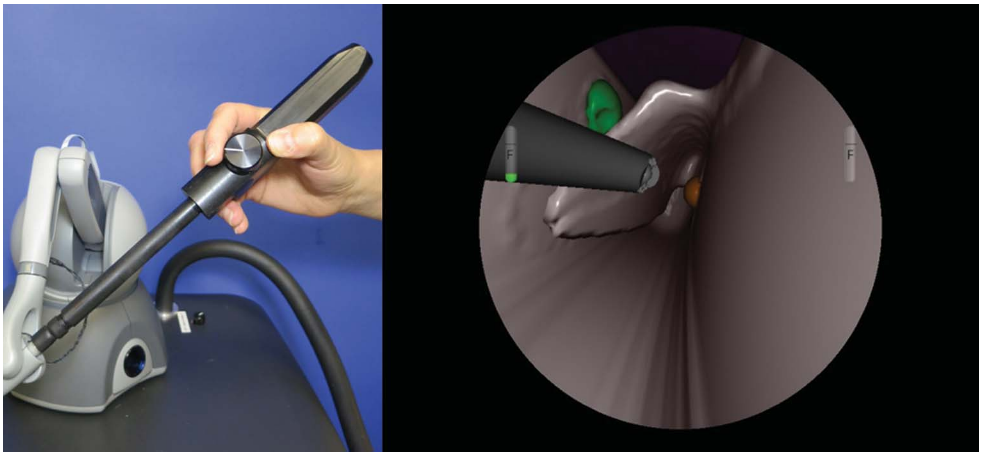

FIGURE 4. *The microdebrider tool handle with the possibility to rotate the virtual instrument tip using a wheel at the thumb. The instrument simulation model functions by first aspirating soft tissue into its opening. The instrument is double serrated; therefore, the aspirated tissue is cut when the inner blade rotates to close the outer opening.*

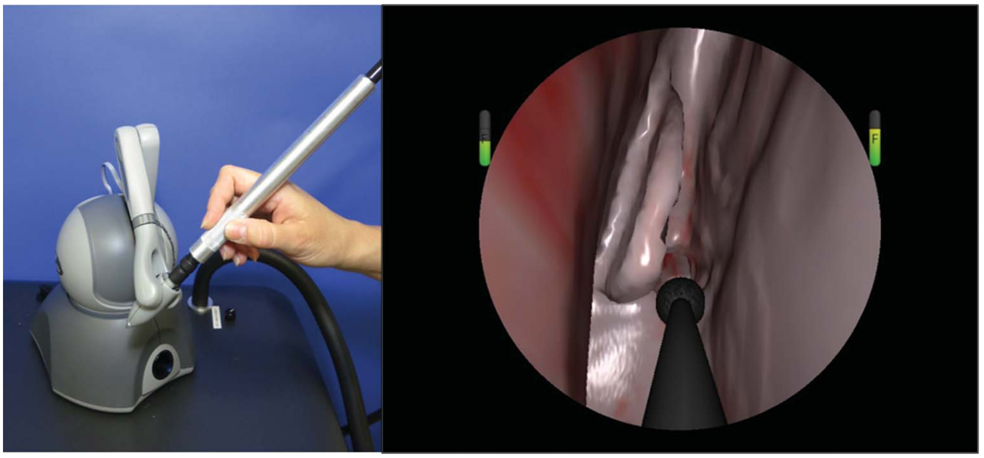

FIGURE 5. *The microdrill model in NeuroTouch is available with a typical physical handle that is cylindrical in shape. The virtual instrument consists of a spherical drill burr with an adjustable drilling power via a knob on the simulator console.*

instruments. The 2-nostril approach initiates the approach through 1 nare to reach the sphenoid ostium, moves to the second nare to identify the second sphenoid ostium, and then works bimanually to connect the 2, completing the approach. For the sellar portion of the procedure, including tumor removal, the endoscope is maintained in 1 nostril while the dissecting instruments move in and out of both nostrils, as needed (see **Video, Supplemental Digital Content 2**, which demonstrates the 2 nostril approach in that the endoscope is "parked" on 1 nostril while dissection proceeds through 1 or both nostrils, http://www.youtube.com/watch?v=77MJ4M3dwX8).

DISCUSSION

Over the past 5 years, we developed a simulator for craniotomy-based procedures. Approximately 20% of cranial surgery done in teaching hospitals is performed via a transsphenoidal approach, and the number of cranial base surgery cases deemed appropriate for an expanded transsphenoidal approach is increasing (E. R. Laws, personal communication, 2011). This created an impetus for the development of VR simulators for these approaches, with

TABLE 2. **FNS Endoscopic Nasal Navigation Training Scenario With Task to Locate the Ostia of the Sphenoid Sinus**[a]

	Conceptual Module	Implemented in NeuroTouch
Learning objectives	1. Handling an endoscope with indirect view onscreen	✓
	2. Recognizing nasal anatomic landmarks	✓
	3. Demonstrating bimanual coordination	✓
Intended user	PGY-3 neurosurgery resident or any person desiring to practice endoscopic skills	
Instructions	Use endoscope and retractor to navigate along the nasal cavity until ostia of the sphenoid sinus are located	✓
Level of difficulty	Easy: normal anatomy, anatomic labels present	✓
	Intermediate: septal deviation, prelateralized middle turbinates, anatomic labels present	✓
	Advanced: normal anatomy, intact turbinates, no anatomic labels	
Performance metrics	Outcome	
	■ Were the sphenoid ostia located? (pass/fail)	✓
	Efficiency	
	■ Distance traveled to reach ostia	✓
	■ Time taken to reach ostia	✓
	Errors	
	■ Number of times excessive force was applied	✓
	■ Time that tool tip not in view	

[a]Adapted from Choudhury et al.[47]

TABLE 3. FNS Endoscopic Nasal Navigation Training Scenario With Task Enter the Sphenoid Sinus

	Conceptual Module	Implemented in NeuroTouch
Learning objectives	1. Handling an endoscope with indirect view onscreen	✓
	2. Recognizing nasal and sphenoid anatomic landmarks	✓
	3. Demonstrating bimanual coordination	✓
Intended user	PGY-3 neurosurgery resident or any person desiring to practice endoscopic skills	
Instructions	Use endoscope and drill to navigate along the nasal cavity until ostium of the sphenoid sinus is located Enlarge the opening and enter the sinus	✓
Level of difficulty	Easy: 1-nostril technique, normal anatomy, anatomic labels present	✓
	2-nostril technique, normal anatomy, anatomic labels present	✓
	Intermediate: septal deviation, prelateralized turbinates, anatomic labels present	
	Advanced: normal anatomy, intact turbinates, no anatomic labels	
Performance metrics	Outcome	
	■ Were the sphenoid ostia located? (pass/fail)	✓
	■ Was the sellar floor visualized?	✓
	Efficiency	
	■ Distanced travelled to reach sellar floor	✓
	■ Time taken to reach sellar floor	✓
	Errors	
	■ Number of times excessive force was applied	✓
	■ Time that tool tip not in view	
	■ Removal/damage to tissue normally not to be touched	

an ultimate goal to establish a VR training curriculum for neurosurgery residents. Building on the foundation previously described over the past 3 years, we developed a simulator for endoscopic endonasal procedures. Previous experience with neurosurgeons in the advisory network of our teaching hospitals showed that early versions of our VR simulator for neurosurgery were most praised for their visual content and most criticized for touch, with the majority of suggestions focused on ergonomics. Future improvements will focus on these aspects of the device.

The next steps in the development of training tasks will include obtaining comments and metrics from use of the endonasal anatomy program. Metrics from the use of an ethmoidectomy task for otorhinolaryngology residents will be used to develop sphenoidectomy and sellar exploration tasks, as well as extended transsphenoidal exposures. Tool trajectory analysis metrics may be implemented to assess the metrics of efficiency of cleansing the endoscope, smoothness of movement, and bimanual coordination.

These psychomotor skills training modules will continue to require linkage with a continually updated didactic, cognitive component to provide complete neurosurgeon training. Initial studies demonstrated improved performance on the craniotomy performance tool, with neurosurgery residents performing better than medical students.[47] Further stratification of expertise and documentation of improvement is ongoing.[50,51]

Future Directions

In addition to training resident neurosurgeons, the use of NeuroTouch could potentially be extended to patient-specific rehearsals before surgery. Such future uses could be accomplished through the development of a high-speed data-processing pipeline to convert magnetic resonance and computed tomography images into simulation models.

CONCLUSION

NeuroTouch is a virtual simulator with haptic feedback that offers promise for enhancing the educational curricula for teaching endonasal endoscopic transsphenoidal surgery to neurosurgeons. The potential advantages include cost because the system can be used an unlimited number of times once purchased, unlike cadavers. The device may ultimately demonstrate both efficiency and reliability in depicting the endonasal operative corridor in the living patient as well as potentially provide for training in pathological variance. Metrics are being developed for validation studies with neurological residents.

Disclosure

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REFERENCES

1. Aggarwal R, Ward J, Balasundaram I, Sains P, Athanasiou T, Darzi A. Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. *Ann Surg.* 2007;246(5):771-779.

2. Alaraj A, Lemole MG, Finkle JH, et al. Virtual reality training in neurosurgery: review of current status and future applications. *Surg Neurol Int.* 2011;2:52.
3. Apuzzo ML. Virtual neurosurgery: forceps, scissors, and suction meet the microprocessor, rocket science, and nuclear physics. *Neurosurgery*. 2009;64(5):785.
4. Apuzzo ML, Elder JB, Liu CY. The metamorphosis of neurological surgery and the reinvention of the neurosurgeon. *Neurosurgery*. 2009;64(5):788-795.
5. de Notaris M, Solari D, Cavallo LM, et al. The use of a three-dimensional novel computer-based model for analysis of the endonasal endoscopic approach to the midline skull base. *World Neurosurg.* 2011;75(1):106-113; discussion 36-40.
6. Alaraj A, Charbel FT, Birk D, et al. Role of cranial and spinal virtual and augmented reality simulation using immersive touch modules in neurosurgical training. *Neurosurgery*. 2013;72(suppl 1):115-123.
7. Chan S, Conti F, Salisbury K, Blevins NH. Virtual reality simulation in neurosurgery: technologies and evolution. *Neurosurgery*. 2013;72(suppl 1):154-164.
8. Kockro RA, Hwang PY. Virtual temporal bone. An interactive 3-dimensional learning aid for cranial base surgery. *Neurosurgery*. 2009;64(5 suppl 2):216-229.
9. Kockro RA, Stadie A, Schwandt E, et al. A collaborative virtual reality environment for neurosurgical planning and training. *Neurosurgery*. 2007;61(5 suppl 2):379-391.
10. Kockro RA, Serra L, Tseng-Tsai Y, et al. Planning and simulation of neurosurgery in a virtual reality environment. *Neurosurgery*. 2000;46(1):118-135.
11. Lemole GM Jr, Banerjee PP, Luciano C, Neckrysh S, Charbel FT. Virtual reality in neurosurgical education: part-task ventriculostomy simulation with dynamic visual and haptic feedback. *Neurosurgery*. 2007;61(1):142-148.
12. Reznick RK, MacRae H. Teaching surgical skills: changes in the wind. *N Engl J Med.* 2006;355(25):2664-2669.
13. Seymour NE, Gallagher AG, Roman SA, et al. Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Ann Surg.* 2002;236(4):458-463.
14. Tsuda S, Scott D, Doyle J, Jones DB. Surgical skills training and simulation. *Curr Probl Surg.* 2009;46(4):271-370.
15. Wiet GJ, Stredney D. Update on surgical simulation: the Ohio State University experience. *Otolaryngol Clin North Am.* 2002;35(6):1283-1288, viii.
16. Babineau TJ, Becker J, Gibbons G, et al. The cost of operative training for surgical residents. *Arch Surg.* 2004;139(4):366-369.
17. Delorme S, Laroche D, DiRaddo R, Del Maestro RF. NeuroTouch: a physics-based virtual simulator for cranial microneurosurgery training. *Neurosurgery*. 2012;71(1 suppl operative):32-42.
18. Frost & Sullivan. Return on investment study for medical simulation training. 2004. Available at: http://www.healthleadersmedia.com/content/138774.pdf.
19. Francis NK, Hanna GB, Cresswell AB, Carter FJ, Cuschieri A. The performance of master surgeons on standard aptitude testing. *Am J Surg.* 2001;182(1):30-33.
20. Gallagher AG, Ritter EM, Satava RM. Fundamental principles of validation and reliability: rigorous science for the assessment of surgical education and training. *Surg Endosc.* 2003;17(10):1525-1529.
21. Gurusamy K, Aggarwal R, Palanivelu L, Davidson BR. Systematic review of randomized controlled trials on the effectiveness of virtual reality training for laparoscopic surgery. *Br J Surg.* 2008;95(9):1088-1097.
22. Jagannathan J, Vates GE, Pouratian N, et al. Impact of the Accreditation Council for Graduate Medical Education work-hour regulations on neurosurgical resident education and productivity. *J Neurosurg.* 2009;110(5):820-827.
23. Stone S, Bernstein M. Prospective error recording in surgery: an analysis of 1108 elective neurosurgical cases. *Neurosurgery*. 2007;60(6):1075-1080.
24. Jho HD, Carrau RL. Endoscopy assisted transsphenoidal surgery for pituitary adenoma. Technical note. *Acta Neurochir (Wien).* 1996;138(12):1416-1425.
25. Snyderman C, Kassam A, Carrau R, Mintz A, Gardner P, Prevedello DM. Acquisition of surgical skills for endonasal skull base surgery: a training program. *Laryngoscope*. 2007;117(4):699-705.
26. Tabaee A, Anand VK, Fraser JF, Brown SM, Singh A, Schwartz TH. Three-dimensional endoscopic pituitary surgery. *Neurosurgery*. 2009;64(5 suppl 2):288-293.
27. Thapar K, Laws ER. Pituitary surgery. In: Thapar K, Kovacs K, Scheithauer BW, Lloyd RV eds. *Diagnosis and Management of Pituitary Tumors*. Totowa, NJ: Humana Press; 2001:225-246.
28. Wolfsberger S, Neubauer A, Bühler K, et al. Virtual endoscopy is useful device for training and preoperative planning of transsphenoidal endoscopic pituitary surgery. *Minim Invasive Neurosurg.* 2004;47(4):214-220.
29. Kassam AB, Gardner P, Snyderman C, Mintz A, Carrau R. Expanded endonasal approach: fully endoscopic, completely transnasal approach to the middle third of the clivus, petrous bone, middle cranial fossa, and infratemporal fossa. *Neurosurg Focus.* 2005;19(1):E6.
30. Neubauer A, Wolfsberger S, Forster MT, Mroz L, Wegenkittl R, Bühler K. Advanced virtual endoscopic pituitary surgery. *IEEE Trans Vis Comput Graph.* 2005;11(5):497-507.
31. Malone HR, Syed ON, Downes MS, D'Ambrosio AL, Quest DO, Kaiser MG. Simulation in neurosurgery: a review of computer-based simulation environments and their surgical applications. *Neurosurgery*. 2010;67(4):1105-1116.
32. Marcus H, Vakharia V, Kirkman MA, Murphy M, Nandi D. Practice makes perfect? The role of simulation-based deliberate practice and script-based mental rehearsal in the acquisition and maintenance of operative neurosurgical skills. *Neurosurgery*. 2013;72(suppl 1):A124-A130.
33. Moulton CA, Dubrowski A, Macrae H, Graham B, Grober E, Reznick R. Teaching surgical skills: what kind of practice makes perfect? A randomized, controlled trial. *Ann Surg.* 2006;244(3):400-409.
34. Sekhar LN, Tariq F, Kim LJ, Pridgeon J, Hannaford B. Commentary: virtual reality and robotics in neurosurgery. *Neurosurgery*. 2013;72(suppl 1):1-6. doi: 10.1227/NEU.0b013e31827db647.
35. Wolfsberger S, Neubauer A, Bühler K, et al. Advanced virtual endoscopy for endoscopic transsphenoidal pituitary surgery. *Neurosurgery*. 2006;59(5):1001-1009.
36. Raappana A, Koivukangas J, Pirilä T. 3D modeling-based surgical planning in transsphenoidal pituitary surgery—preliminary results. *Acta Otolaryngol.* 2008;128(9):1011-1018.
37. Talala T, Pirilä T, Karhula V, Ilkko E, Suramo I. Preoperative virtual endoscopy and three-dimensional imaging of the surface landmarks of the internal carotid arteries in trans-sphenoidal pituitary surgery. *Acta Otolaryngol.* 2000;120(6):783-787.
38. Bernardo A, Preul MC, Zabramski JM, Spetzler RF. A three-dimensional interactive virtual dissection model to simulate transpetrous surgical avenues. *Neurosurgery*. 2003;52(3):499-505.
39. Brown SM, Tabaee A, Singh A, Schwartz TH, Anand VK. Three-dimensional endoscopic sinus surgery: feasibility and technical aspects. *Otolaryngol Head Neck Surg.* 2008;138(3):400-402.
40. Ferroli P, Tringali G, Acerbi F, et al. Advanced 3-dimensional planning in neurosurgery. *Neurosurgery*. 2013;72(suppl 1):54-62.
41. Ferroli P, Tringali G, Acerbi F, Aquino D, Franzini A, Broggi G. Brain surgery in a stereoscopic virtual reality environment: a single institution's experience with 100 cases. *Neurosurgery*. 2010;67(3 suppl operative):ons79-ons84.
42. Fried MP, Sadoughi B, Gibber MJ, et al. From virtual reality to the operating room: the endoscopic sinus surgery simulator experiment. *Otolaryngol Head Neck Surg.* 2010;142(2):202-207.
43. Spicer MA, Apuzzo ML. Virtual reality surgery: neurosurgery and the contemporary landscape. *Neurosurgery*. 2003;52(3):489-497.
44. Spicer MA, van Velsen M, Caffrey JP, Apuzzo ML. Virtual reality neurosurgery: a simulator blueprint. *Neurosurgery*. 2004;54(4):783-798.
45. Cappabianca P, Alfieri A, de Divitiis E. Endoscopic endonasal transsphenoidal approach to the sella: towards functional endoscopic pituitary surgery (FEPS). *Minim Invasive Neurosurg.* 1998;41(2):66-73.
46. Carrau RL, Jho HD, Ko Y. Transnasal-transsphenoidal endoscopic surgery of the pituitary gland. *Laryngoscope*. 1996;106(7):914-918.
47. Choudhury N, Gélinas-Phaneuf N, Delorme S, Del Maestro R. Fundamentals of neurosurgery: virtual reality tasks for training and evaluation of technical skills [published online ahead of print]. *World Neurosurg.* 2012. pii: S1878-8750(12)01359-9.
48. Ericsson KA. Deliberate practice and acquisition of expert performance: a general overview. *Acad Emerg Med.* 2008;15(11):988-994.

49. Ericsson KA. An expert-performance perspective of research on medical expertise: the study of clinical performance. *Med Educ.* 2007;41(12):1124-1130.
50. Gélinas-Phaneuf N, Del Maestro R. *Technical Skills Expertise in Neurosurgery: Integrating Theory Into Practice*. (In press).
51. Gélinas-Phaneuf N, Okrainec A, Fried GM, Choudhury N, Del Maestro RF. *The Assessment of Technical Skills in Neurosurgery: The Development of the Global Assessment of Intraoperative Neurosurgical Skills (GAINS) Scale*. (Unpublished Work). Montreal, Canada: McGill University; 2013.
52. Gélinas-Phaneuf N, Okrainec A, Fried GM, Choudhury N, Del Maestro RF. The assessment of technical skills in neurosurgery: the development of the global assessment of intraoperative neurosurgical skills (GAINS) Scale. Paper presented at: Canadian Conference on Medical Education (Poster); May 2010; Saint-John's, Newfoundland.
53. Bakker NH, Fokkens WJ, Grimbergen CA. Investigation of training needs for functional endoscopic sinus surgery (FESS). *Rhinology*. 2005;43(2):104-108.

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