A physical simulator for endoscopic endonasal drilling techniques: technical note

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In this paper, the authors present a physical model developed to teach surgeons the requisite drilling techniques when using an endoscopic endonasal approach (EEA) to the skull base. EEA is increasingly used for treating pathologies of the ventral and ventrolateral cranial base. Endonasal drilling is a unique skill in terms of the instruments used, the long reach required, and the restricted angulation, and gaining competency requires much practice. Based on the successful experience in creating custom simulators, the authors used 3D printing to build an EEA training model from post-processed thin-cut head CT scans, formulating the materials to provide realistic haptic feedback and endoscope handling. They performed a preliminary assessment at 2 institutions to evaluate content validity of the simulator as the first step of the validation process. Overall results were positive, particularly in terms of bony landmarks and haptic response, though minor refinements were suggested prior to use as a training device.

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KEY WORDS 3D printing; drilling simulator; endoscopic endonasal approach; diagnostic and operative techniques
The simulator was designed to target drilling practice in exposing the planum sphenoidale, internal carotid artery, optic nerve, sella turcica, and upper clivus. Figure 1 depicts an overall concept of the simulator, which consists of 4 parts: 1) skull frame; 2) replaceable insert for drilling; 3) skin and nasal cavity phantom tissue mask; and 4) optic nerve, pituitary gland, and carotid artery replicas. The anatomical geometry was created based on high-resolution CT images. The replaceable insert design allows for repeated use, as well as different anatomical designs, at lower costs.

The skull frame was made of printable thermal plastic, which provided a strong and durable structure for the simulator. The drilling insert was also created using 3D printing technology with specially formulated plaster composites followed by an epoxy coating to enhance the material strength and to mimic bicortical bone. A slot design in the skull frame allows for rapid assembly and removal. The insert includes relevant anatomical features, such as a pituitary fossa, carotid prominences, and opticocarotid recesses. On the insert are colored artificial internal carotid arteries, optic nerves, and a pituitary gland, providing visual feedback when skeletonizing these structures (Fig. 1B). The face mask reproduces the anatomy of the nasal passage, including the nasal septum, turbinates, and the nares, mimicking the constraints to endoscope and drill movement inherent in endonasal drilling (Fig. 1C). Like the bone-mimicking aspects of the simulator, the mask was produced using molding techniques based on CT images. The silicone material was adapted to simulate nasal tissue rigor for the face mask.

The simulator setup for training allows for use of the same tools and equipment used in surgery, including endoscopes and video tower, drill and drill bits, rongeurs and dissectors, as well as suction and irrigation, if desired. The setup for drilling practice is shown in Fig. 2, along with the endoscope and drilling device. Several images captured during drilling practice are demonstrated in Fig. 3, including sphenoidotomy, skeletonizing carotid arteries and sella turcica, and decompressing the optic nerve. No irrigation was used for this demonstration.

The material cost of this simulator was approximately $500, without counting labor and overhead. Although we had access to our institution’s 3D print facilities, the initial investment on 3D printers could have been from a few thousand to more than $250,000. Manufacturing time for the final prototype was approximately 2 to 3 days, including 3D printing, silicone molding, and assembly. For future use, a large number of inserts (30 or more) can be printed and epoxy-treated within 24 hours, depending on the printer capacity. Note that the final production cost may vary significantly due to the arrangements of automation, equipment, and workforce.

Evaluation of Content Validity

The preliminary evaluation of content validity was
consistent with our prior study on a ventriculostomy simulator. Following review and exempt consideration from the University of Michigan’s institutional review board, a sample of neurosurgeons evaluated the simulator. A sample of 8 neurosurgeons from 2 neurosurgery training programs (University of Michigan, n = 5; and Henry Ford Hospital, n = 3) consisted of both faculty and senior residents who were familiar with EEA. The simulator evaluation began with a brief introduction of the simulator to both sites. Each site then used its own endoscope and drill for individualized, hands-on experience and testing without further instruction. After participants performed the EEA, they completed a 23-item survey using a 4-point rating scale, with 4 being the highest score. The survey form with details, corresponding scores, and major comments are listed in Table 1. Eleven survey items were targeted to measure the opinions of experienced surgeons regarding simulator characteristics and features across 5 domains: physical attributes, realism of experience, value of simulator, relevance to clinical practice, and a global (overall) rating. The preliminary validation process aligned with best practices defined by the current standards framework offered by the American Educational Research Association, American Psychological Association, and National Council on Measurement in Education, while the metrics captured were supported by current literature. Statistical analyses were performed using a many-facet Rasch model to compute average ratings and analyze rating differences across levels of training and training program sites. Inter-item reliability for the 11 targeted items was estimated to be moderately high (α = 0.80).

**Survey Results**
Analyses indicated that the faculty-observed average was higher (3.3 out of 4.0) than the learner-observed average (3.0), but was not statistically significant ($\chi^2 = 0.1$ [df = 1, n = 8]; p = 0.82). The University of Michigan—observed average was higher (3.1) than the Henry Ford Hospital—observed average (3.0) ($\chi^2 = 17.3$ [df = 1, n = 8]; p = 0.01), although the practical difference was negligible. Deeper analysis at the item level indicated no statistical differences across training program sites. Given that rating differences were practically insignificant, data were combined for subsequent analyses and reported as such. In descending order, combined observed averages were found to be 3.83, 3.67, 3.42, 3.34, and 2.80 for the value, relevance, physical attributes, realism of experience, and global (overall) domains, respectively. Value of the simulator obtained the highest score of 3.83, indicating this model had high potential for serving as a training tool. The global observed average of 2.80 aligned with “This simulator requires minor adjustments before it can be considered for use in EEA drilling training.” These findings were consistent with suggestions for improvement that included enlargement of the nostrils, softening of the nasal tissue, and decreasing the physical gap between the posterior portion of the turbinates and sphenoid. Inter-item reliability for the 11 targeted items was estimated to be moderately high (α = 0.80).

**Discussion**
Neurosurgical leadership has made a concerted effort in recent years to explore specific areas in which simulation can be effectively used to enhance neurosurgical training. Several peculiarities inherent in the EEA make existing educational supplements irrelevant for training in endonasal drilling. First, the hand skills used in drilling and dissection are not replicated by almost any other ne-
rosurgical operation. This is largely due to the restricted angulation and movement enforced by the nares and nasal structures and is exacerbated by the presence of the endoscope and any other instruments in the field. Second, the instruments typically used in performing the EEA are rarely used otherwise, are modified for the approach, or are used in other neurosurgical procedures but in a vastly different manner from their use in EEA procedures. For example, drill bits are extended and frequently curved to accommodate the EEA. In addition, the axis of rotation at which instruments are pivoted is necessarily at the nares with the EEA, whereas the pivoting occurs either at the distal end or near the proximal end of instruments in a large majority of situations in neurosurgery. Third, visualization using endoscopy is otherwise rare in neurosurgery. Familiarity with its use is gained only through repetition, and this repetition is ideally gained outside of the operating room. Fourth, this region involves, in places, thin bone adjacent to critical neural and vascular structures. Whereas in other operations, trainees can be allowed to gain technical experience by drilling away from more critical structures, there are few such low-risk regions for training, as inexpensively as possible, and to address the aforementioned challenges in learning the EEA. Using thin-slice CT images and 3D printing technology, we are able to produce craniofacial models with submillimeter accuracy, based on realistic anatomical landmarks. Similarly, the variety of models that can be created is limited only by the availability of images from different patients. Preoperative CT images from specific patients can be made into drilling models with a moderate amount of postprocessing. As with cadaveric training, the same instruments used in surgery are used for practice, which is ostensibly advantageous, especially given the relatively unique aspects of the EEA.

The most important and challenging aspect of creating this simulator came in formulating the materials to mimic bone. The sphenoid bone consists of areas that are bicortical, and others that are so thin that little or no cancellous bone exists. In addition, there is a great deal of variability from patient to patient and, thus, our methods must be able to reflect this variability. We chose to use a plaster-based material for 3D printing, which can be coated with various epoxy resins to reflect the drilling properties of cancellous bone. This formulation was easy to produce, and observed average ratings indicated the sensory feedback during drilling was adequately lifelike (Table 1).

The inherent limitations of our simulator are primarily in the materials used. Despite a large number of trials taken to finalize the formulations, they could be further improved to address the weakness in soft tissue. We also anticipate another limitation in the implementation of our simulator for surgical training, i.e., the acquisition of an endoscopy tower and drill. This will be influenced by the program directors’ commitment to using simulation as a training mechanism at their institution.

Furthermore, the simulator’s current features are somewhat limited. The simulator could be made more sophisticated in several ways. For example, we could replicate a variety of nostril sizes and stiffness, and add the bleeding feature with minor modifications. Additional functions, such as capturing of objective performance measures, also could be added by embedding sensors (e.g., in the optic canals and internal carotid arteries) to alarm when overheating and/or mechanical damage occurs. With the flexibility of 3D printing, customized features and functions can be available. The next step in the simulator’s development will be seeking a commercialization partner for broader implementation.

### TABLE 1. Results of content validity evaluation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Observed Average (SD)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical attributes*</td>
<td>3.42 (0.57)</td>
<td>Nostrils too small</td>
</tr>
<tr>
<td>Nostril flexibility</td>
<td>3.50 (0.55)</td>
<td></td>
</tr>
<tr>
<td>Landmark opticocarotid recesses</td>
<td>3.17 (0.75)</td>
<td></td>
</tr>
<tr>
<td>Landmark pituitary fossa</td>
<td>3.50 (0.55)</td>
<td></td>
</tr>
<tr>
<td>Landmark carotid prominences</td>
<td>3.50 (0.55)</td>
<td></td>
</tr>
<tr>
<td>Realism of experience*</td>
<td>3.34 (0.64)</td>
<td></td>
</tr>
<tr>
<td>Response of “bone” during manipulation of endoscope &amp; drills</td>
<td>3.67 (0.52)</td>
<td></td>
</tr>
<tr>
<td>Response of “bone” during drilling of sphenoid bone</td>
<td>3.50 (0.55)</td>
<td></td>
</tr>
<tr>
<td>Response of “nasal tissue” during manipulation of endoscope, suction, &amp; drill</td>
<td>3.00 (0.63)</td>
<td>Nasal tissue too firm</td>
</tr>
<tr>
<td>Endoscopic view</td>
<td>3.17 (0.41)</td>
<td>Gap bwt posterior portion of turbinates &amp; sphenoid is too large</td>
</tr>
<tr>
<td>Value as a training tool†</td>
<td>3.83 (0.41)</td>
<td></td>
</tr>
<tr>
<td>Relevance to clinical practice</td>
<td>3.67 (0.52)</td>
<td></td>
</tr>
<tr>
<td>Global rating‡</td>
<td>2.80 (0.73)</td>
<td></td>
</tr>
</tbody>
</table>

* 1, not at all realistic; 2, lacks too many key features; 3, adequate realism but could be improved; 4, highly realistic, no changes needed. † 0, no value; 1, little value; 3, some value; 4, great value. ‡ 0, needs extensive improvements; 2, needs minor adjustments; 3, needs slight improvement; 4, no improvement needed.
A VR simulator is another option for EEA training. Rosseau et al.11 presented their experience using NeuroTouch to teach the EEA, emphasizing improved haptics and potential cost savings from unlimited use, once purchased. Stredney et al.14 reported on another VR system that provides interactive training of several procedural drilling techniques. VR simulation has advantages in that it is reusable, can be modified and modulated, and most importantly, can provide accurate and detailed visual representation. However, the initial cost of purchase is usually high,12 and computer-generated tactile feedback is still unrealistic.4 Mechanical feedback is affected by a myriad of factors, including bur material (diamond or metal burs), bur fluting, bur diameter, rotational velocity, coefficients of abrasion (coarse or fine burs), and direction of drill rotation and movement.8 VR systems usually calculate forces based on voxel intensity,7 which is unlikely to recreate the nuanced mechanics. In comparison, a physical simulator is better suited for such sensory-focused training, provided the relevant tissue properties can be duplicated. Okuda et al.9 proposed an endoscopic training method using a skull model and eggs. They used the shell to simulate the sella turcica and the egg contents to simulate a tumor. The concept is simple and effective, so long as the egg shell accurately reflects the tissue properties inherent to drilling bone, though the anatomy is not represented. Hybrid models (e.g., the Phacon Sinus System by PHACON; SIMONT by ProDelphus) also exist that combine a virtual environment for visualization and navigation on CT or MR images, as well as a physical part for tool handling and drilling. Initial surveys have been positive,5 but the cost itself may still limit wide adoption.

Lastly, the primary limitation of our research was associated with the small sample size. Although the sample reflected some diversity in experience level across the 2 training programs, the sample size was small, which limits our ability to generalize findings across the broader population of neurosurgeons. Furthermore, this study’s intended scope was targeted to preliminary evaluation of content validity. Future work includes evaluating validity evidence relevant to its application as an effective supplement to neurosurgery training programs.

Conclusions

Since the recent development of EEA, operative videos detailing the procedure have been made available from several sources to supplement educational directives for trainees. While observation and operative video review should be considered requisite in surgical training, the specific skill sets involved in the EEA are unique among neurosurgical operations. The integration of learning gained from observation is dependent upon a preexisting experience—a context in which the observed techniques can be placed. A simulator serves to expand that context by allowing for practice of the hand skills and visual recognition that are not common to other neurological operations. In this regard, a physical simulator is the ideal medium for procedural practice and mastery. Using this simulator, a trainee is afforded the opportunity to gain familiarity with the same instruments used in surgery, under similar limitations in movement and angulation, and to practice drilling on a material that mimics the mechanical feedback from bone extremely closely, molded to recreate human anatomy with submillimeter accuracy. Survey results from 8 surgeons with a range of expertise support the use of this model for training in the EEA, although some refinement will be necessary.

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References


**Disclosure**

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

**Author Contributions**

Conception and design: Tai, AC Wang. Acquisition of data: Tai, AC Wang, Joseph. Analysis and interpretation of data: Drafting the article: Rooney, Tai, AC Wang, PI Wang. Critically revising the article: Tai, McKean. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Rooney. Statistical analysis: Rooney. Study supervision: Sullivan, McKean, Shih.

**Supplemental Information**

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