Development of a 3-Dimensional Middle Ear Model to Teach Anatomy and Endoscopic Ear Surgical Skills

Carolyn M. Jenks, MD1,2, Vir Patel, MD2, Brittany Bennett3,4, Brian Dunham, MD2,4 and Conor M. Devine, MD2,4

Abstract
Mastery of ear anatomy and otologic surgical skills is challenging for trainees, and educational resources are limited. Advancements in 3-dimensional (3D) printing have enabled the construction of complex microscopic models. Otoendoscopy provides excellent visualization and has been shown to enhance anatomic learning. Our aim was to develop a 3D model of the middle ear and external auditory canal using computed tomography images of a pediatric temporal bone for use with otoendoscopes. Resulting models are life-sized, anatomically accurate, and allow for identification of relevant middle ear structures. Forty-six trainees were recruited for a pilot study and randomized to study using the model or standard resources. There were no differences in pretest, posttest, or 1-week posttest performance between groups; however, trainees assigned to the model reported higher prospective interest, satisfaction, and subjective improvement. This model may be used with otoendoscopes for anatomic and surgical training and represents an advancement in otologic surgical simulation.

Keywords
endoscopic ear surgery, 3-dimensional printing, 3D model, simulation, anatomy

Received July 12, 2021; accepted August 27, 2021.

Middle ear anatomy and otologic surgical skills are challenges for otolaryngology trainees. It is critical that students master relationships between structures within the middle ear. Current study aids include 2-dimensional atlases, 3-dimensional (3D) computer models, and cadaveric temporal bones. Two-dimensional study tools fail to adequately capture anatomic relationships, computer models lack fidelity, and human temporal bones are expensive and impractical for routine use.1 Thus, critical learning occurs in the operating room. Improved resources are needed for trainees.

Otoendoscopy provides high-magnification visualization and has been shown to enhance trainees’ understanding of anatomy.2 Ultra-high-definition 3D printing, in combination with otoendoscopy, provides an opportunity to improve on current methods of teaching middle ear anatomy.

The aim of this study was to develop a high-fidelity 3D-printed model of the middle ear. In addition, we aimed to determine whether the use of otoendoscopes and 3D models enhances middle ear anatomy acquisition among early learners.

Methods

Model Development
Thin-cut (0.6-mm) computed tomography images of a pediatric temporal bone were used to generate a 3D model of the middle ear and external auditory canal (Materialise Mimic, Leuven, Belgium). Segmentation from the scan was imported into Pixologic ZBrush (Los Angeles, California, USA) to increase the model’s resolution. Structures not captured on segmentation were sculpted using Maxon Cinema 4D R21 (Friedrichsdorf, Germany). Color application was performed. The model was processed on GrabCAD studios (Cambridge, Massachusetts, USA) and printed on a Stratasys J750 printer (Rehovot, Israel). Color application was performed. The model was processed on GrabCAD studios (Cambridge, Massachusetts, USA) and printed on a Stratasys J750 printer (Rehovot, Israel). Excluding initial design fees, individual models cost $136.

1Department Otolaryngology–Head & Neck Surgery, Johns Hopkins University School of Medicine, Baltimore, Maryland, USA
2Department of Otorhinolaryngology–Head and Neck Surgery, Hospital of the University of Pennsylvania, Philadelphia, USA
3Department of Radiology, Children’s Hospital of Philadelphia, Philadelphia, USA
4Division of Otolaryngology, Children’s Hospital of Philadelphia, Philadelphia, USA

This article was presented as a poster presentation at the AAO-HNSF Annual Meeting & OTO EXPO; September 13, 2020; Boston, Massachusetts.

Corresponding Author:
Carolyn M. Jenks, MD, Department Otolaryngology–Head & Neck Surgery, Johns Hopkins University School of Medicine, Baltimore, Maryland, 610 N. Caroline St, 6th Floor, Baltimore, MD 21287, USA
Email: cjenks@jhmi.edu

This Creative Commons Non Commercial CC BY-NC: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial 4.0 License (http://creativecommons.org/licenses/by-nc/4.0/) which permits non-commercial use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
Pilot Study Design
Exemption was granted from the Institutional Review Board at the Children’s Hospital of Philadelphia for a pilot study to examine the use of the model for teaching anatomy. Medical students and first- through third-year residents were randomized into 2 groups that contained equal numbers of trainees at each level. Trainees were assigned to study middle ear anatomy using the model and 0° and 30° rigid endoscopes (Karl Storz, Tuttingen, Germany) along with a written anatomic guide (Supplemental Materials 1) or the written guide in addition to dissection manuals, atlases, and teaching videos (“standard materials”). Participants had 45 minutes of supervised study time. Participants completed a test of middle ear anatomy, adapted from Anschuetz et al (Supplemental Materials 2) before, immediately after, and 1 week after the study period.² A Likert-type scale scored from 1 to 5 was used to survey the interest level of the participants before the self-study period and satisfaction and subjective improvement levels after completing the posttest.

Data were analyzed using Stata v11 (StataCorp, College Station, Texas, USA). Student t tests were used to compare results between groups.

Results
Middle Ear Model
The model includes color-coded structures and spaces: malleus, incus, stapes, cochleariform process, tensor tympani muscle and tendon, stapedial tendon, tympanic segment of facial nerve, chorda tympani, Eustachian tube orifice, and sinus tympani (Figures 1 and 2).

Pilot Study
Thirty-two students and 14 residents participated. Residents performed significantly better on pretests (63% vs 30%), posttests (81% vs 56%), and 1-week posttests (79% vs 53%) compared with students (all P < .001). There were no differences in scores or changes in performance on tests between trainees using the model compared with those using standard materials (Table 1).

Prospective interest in the assigned method (4 vs 2.7, P < .001), retrospective satisfaction (4 vs 2.6, P < .001), and subjective improvement (3.5 vs 2.9, P = .02) levels was higher among trainees assigned to the model as compared with controls (Table 1).

Discussion
We developed a reproducible, reusable, inexpensive, life-sized, anatomically accurate 3D model of the middle ear. In a pilot study, trainees studied anatomy using either the model and otoendoscope or standard materials; both groups also accessed a detailed anatomy guide. We hypothesize that the guide masked benefits conferred by the 3D model; hence, no differences in performance were found between groups. Trainees using the model reported higher interest, satisfaction, and subjective improvement levels.

Advancements in otoendoscopy and high-definition 3D printing have the potential to revolutionize instruction of anatomy and endoscopic surgical skills.³ Multiple 3D-printed models have been developed as an inexpensive and high-fidelity alternative to cadaveric specimens for simulating mastoidectomy.⁴-⁷ Because of the complex relationships of microscopic structures in a small space, 3D printing of the
middle ear is more challenging. Although 3D models have been developed for otoendoscopic middle ear surgical training, none have included the detailed middle ear anatomy required for anatomic teaching.8,9 Otoendoscopy provides high-definition, high-magnification visualization of the middle ear space and has been shown to enhance learners’ understanding of anatomy in surgical and cadaveric lab settings.2,10 A single-center study conducted in Switzerland that used proctored dissection of a cadaveric middle ear demonstrated enhanced learning using otoendoscopy compared with microscopy.2 However, the use of one-on-one tutoring and cadavers renders these methods impractical for everyday use. The model presented here is color coded and may be paired with a dissection manual for independent study. The model is reproducible, reusable, and inexpensive, making it practical for widespread use. This represents an advancement in the use of 3D printing and otoendoscopy for anatomic teaching. This model also provides an opportunity for otoendoscopic surgical skills training and will be developed for this purpose.

**Conclusion**

Our team of artists, engineers, and otolaryngologists developed a reproducible, reusable, and realistic 3D-printed model of the middle ear. Trainees who used the 3D model and endoscopes to study middle ear anatomy reported higher interest and satisfaction levels. This model represents an advancement in otologic surgical simulation to be used for both anatomic teaching and otoendoscopic surgical skills acquisition.

**Acknowledgments**

The authors acknowledge Elizabeth Silvestro, MSE, from the Children’s Hospital of Philadelphia Children’s Hospital Additive Manufacturing for Pediatrics (CHAMP) lab, for her work on the 3D model and Eo Trueblood, MA, lead illustrator at the Children’s Hospital of Philadelphia Stream Studios, for artwork included in the supplemental anatomic guide.

**Author Contributions**

Carolyn M. Jenks, substantial contributions to conception and design, acquisition of data, and analysis and interpretation of data; drafting the article; final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; Vir Patel, substantial contributions acquisition of data; revising the article critically for important intellectual content; final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; Brittany Bennett, substantial contributions to conception and design; revising the article critically for important intellectual content; final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; Brian Dunham, substantial contributions to conception and design; revising the article critically for important intellectual content; final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved; Conor M. Devine, substantial contributions to conception and design and interpretation of data; revising the article critically for important intellectual content; final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

**Disclosures**

**Competing interests:** None.

**Sponsorships:** None.

**Funding source:** Funding was received from the University of Pennsylvania Department of Otorhinolaryngology–Head and Neck Surgery Pilot Grant Program.

**ORCID iD**

Carolyn M. Jenks [https://orcid.org/0000-0001-7166-2966](https://orcid.org/0000-0001-7166-2966)

**Supplemental Material**

Additional supporting information is available at [http://journals.sagepub.com/doi/suppl/10.1177/2473974X211046598](http://journals.sagepub.com/doi/suppl/10.1177/2473974X211046598).

**References**

1. Mills R, Lee P. Surgical skills training in middle-ear surgery. *J Laryngol Otol*. 2003;117(3):159-163.
2. Anschuetz L, Huwendiek S, Stricker D, Yacoub A, Wimmer W, Caversaccio M. Assessment of middle ear anatomy teaching methodologies using microscopy versus endoscopy: a randomized comparative study. *Anat Sci Educ*. 2019;12(5):507-517.

3. VanKoevering KK, Hollister SJ, Green GE. Advances in 3-dimensional printing in otolaryngology: a review. *JAMA Otolaryngol Head Neck Surg*. 2017;143(2):178-183.

4. Gadaleta DJ, Huang D, Rankin N, et al. 3D printed temporal bone as a tool for otologic surgery simulation. *Am J Otolaryngol*. 2020;41(3):102273.

5. Wong V, Unger B, Pisa J, Gousseau M, Westerberg B, Hochman JB. Construct validation of a printed bone substitute in otologic education. *Otol Neurotol*. 2019;40(7):e698-e703.

6. Roosli C, Sim JH, Mockel H, Mokosch M, Probst R. An artificial temporal bone as a training tool for cochlear implantation. *Otol Neurotol*. 2013;34(6):1048-1051.

7. Probst R, Stump R, Mokosch M, Roosli C. Evaluation of an infant temporal-bone model as training tool. *Otol Neurotol*. 2018;39(6):e448-e452.

8. Dedmon MM, O’Connell BP, Kozin ED, et al. Development and validation of a modular endoscopic ear surgery skills trainer. *Otol Neurotol*. 2017;38(8):1193-1197.

9. Barber SR, Kozin ED, Dedmon M, et al. 3D-printed pediatric endoscopic ear surgery simulator for surgical training. *Int J Pediatr Otorhinolaryngol*. 2016;90:113-118.

10. Kutz JW Jr. Introduction to endoscopic ear surgery [lecture]. Presented at: University of Pennsylvania Temporal Bone Course; February 23, 2019; Philadelphia, PA.