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Middle Cranial Fossa Approach to Repair Tegmen Defects Assisted by Three-Dimensionally Printed Temporal Bone Models

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Objectives/Hypothesis: To explore the perioperative utility of three-dimensionally (3D)-printed temporal bone models of patients undergoing repair of lateral skull base defects and spontaneous cerebrospinal fluid leaks with the middle cranial fossa approach.

Study Design: Case series.

Methods: 3D-printed temporal bone models—based on patient-specific, high-resolution computed tomographic imaging—were constructed using inexpensive polymer materials. Preoperatively, the models demonstrated the extent of temporal lobe retraction necessary to visualize the proposed defects in the lateral skull base. Also preoperatively, Silastic sheeting was arranged across the modeled tegmen, marked, and cut to cover all of the proposed defect sites. The Silastic sheeting was then sterilized and subsequently served as a precise intraoperative template for a synthetic dural replacement graft. Of note, these grafts were customized without needing to retract the temporal lobe.

Results: Five patients underwent the middle cranial fossa approach assisted by 3D-printed temporal bone models to repair tegmen defects and spontaneous cerebrospinal fluid leaks. No complications were encountered. The prefabricated dural repair grafts were easily placed and fit precisely onto the middle fossa floor without any additional modifications. All defects were covered as predicted by the 3D temporal bone models. At their postoperative visits, all five patients maintained resolution of their spontaneous cerebrospinal fluid leaks.

Conclusions: Inexpensive 3D-printed temporal bone models of tegmen defects can serve as beneficial adjuncts during lateral skull base repair. The models provide a panoramic preoperative view of all tegmen defects and allow for custom templating of dural grafts without temporal lobe retraction.

Key Words: Tegmen defect, skull base repair, 3D-printed temporal bone model, middle cranial fossa approach.

Level of Evidence: 4

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INTRODUCTION

Defects in the lateral skull base (tegmen mastoideum and tegmen tympani) can be associated with cerebrospinal fluid (CSF) leakage and temporal encephalocele formation, which increase the risk of meningitis in addition to causing aural fullness, pulsatile tinnitus, or conductive hearing loss.[1–3] Defects in the tegmen may be caused by trauma, chronic otitis media, erosive neoplastic disease, or most commonly, spontaneous idiopathic processes. For patients with spontaneous defects, gradual erosion of the tegmen from pulsations of the dura in patients with high intracranial pressures or aberrant arachnoid granulation formations through the middle fossa or posterior fossa plates are thought to be the underlying mechanisms.[4,5] The role of obesity in the development of spontaneous CSF otorrhea has been more closely examined, as Kutz et al. found that this condition is more common in obese female patients.[6] Stevens et al. identified a statistically significant radiographic association of tegmen dehiscence in obese patients.[7] Perhaps not coincidentally, the incidence of spontaneous CSF leaks, temporal encephaloceles, and tegmen dehiscences appears to be increasing with the obesity epidemic.[8]

Tegmen defects can be repaired via one of three approaches: transmastoid, middle cranial fossa, or a combined transmastoid–middle fossa approach.[9] The transmastoid approach avoids a craniotomy and provides sufficient exposure for posterolateral tegmen mastoideum defects. However, for larger defects or those extending to the tegmen tympani or exposing the ossicular heads, the transmastoid approach fails to provide adequate exposure. The middle cranial fossa approach provides access to the entire lateral skull base, including regions medial to the ossicular heads or anteriorly near the petrous apex. The main disadvantage of the middle fossa approach is that it requires a craniotomy, which increases the risk of

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There are currently no conflicts of interest, but we have a patent pending for peripherally related work involving lateral skull base repair and three-dimensional printed technology.

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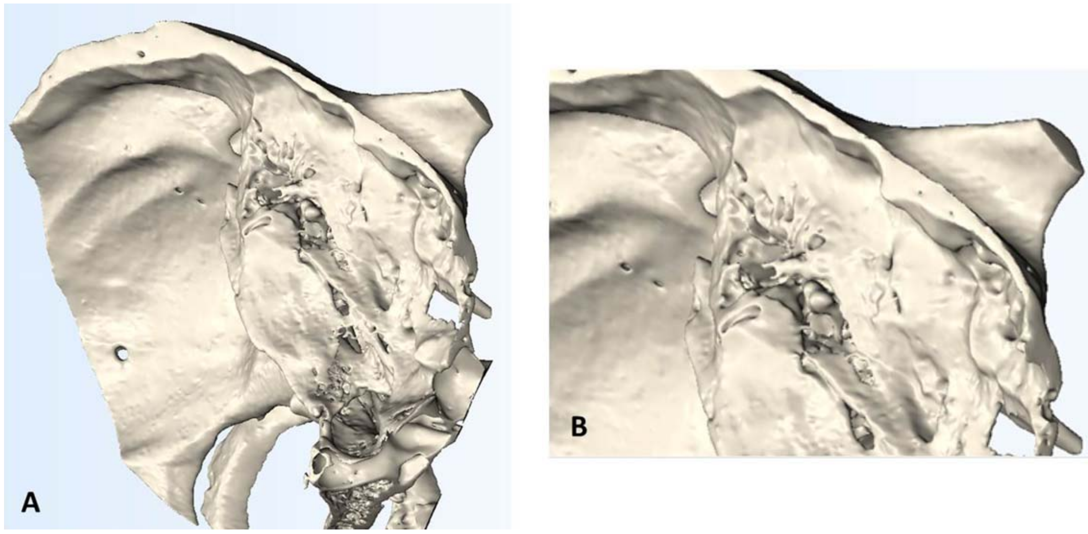

Fig. 1. Computer-aided design of a temporal bone model with multiple tegmen mastoideum and tegmen tympani defects in the left lateral skull base for patient 2. (A) Low-power view and (B) high-power view. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

dural tears, subdural or epidural hematoma formation, meningitis, and temporal lobe injury.[9,10] Many factors are important when selecting the approach, including age, comorbidities, history of prior repairs, and preexisting hearing loss. Both autologous and alloplastic graft materials have been successfully used to repair lateral skull base defects. However, sculpting these grafts to fit a patient's specific skull base anatomy remains a challenging and often time-consuming part of the repair.[6,11–14]

We hypothesized that three-dimension (3D) printing could be utilized to improve the preoperative planning and expedite the fashioning of the grafts placed intraoperatively. 3D printing has allowed for rapid, cost-effective fabrication of patient-specific, highly complex models in various fields.[15,16] Temporal bone models have been previously created with 3D printing technology primarily as simulation models to enhance resident education.[17,18] However, to date, there are no reports of 3D-printed patient-specific temporal bone models to improve preoperative preparation and surgical repair. We describe the use of low-cost 3D-printed temporal bone models to be used as templates to preoperatively customize synthetic dural replacement grafts and intraoperatively verify that all tegmen defects and near-dehiscent sites have been addressed.

MATERIALS AND METHODS

A retrospective review was performed of patients who underwent the middle cranial fossa approach to repair tegmen defects assisted by 3D-printed temporal bone models. The institutional review board at the University of Michigan approved this study (HUM00108678). All surgeries were performed by the senior surgeon (H.A.A.) at a single tertiary care institution.

Preparation of 3D-Printed Temporal Bone Models

Preoperatively, all patients underwent high-resolution computed tomographic (CT) imaging (0.625-mm slices). The digital imaging and communication (DICOM) images from each CT scan were then uploaded into a 3D modeling and segmentation program (Mimics; Materialise, Leuven, Belgium). The DICOM images were segmented using the thresholding function isolating the Hounsfield units consistent with the temporal bone. A 3D model of each patient's temporal bone was then generated (Fig. 1). The temporal bones for each patient were then 3D printed on a fused deposition modeling (FDM) printer at a layer thickness of 100 μm using polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS; Fig. 2). These materials are inexpensive and readily available with most consumer and commercial grade FDM printers.

Preparation of Synthetic Dural Grafts

The 3D-printed temporal bone model displayed all of the frankly dehiscent sites and nearly dehiscent sites in the tegmen. This tangible, panoramic view of the lateral skull base provided the surgeon an understanding of the extent of craniotomy and temporal lobe retraction required to visualize all of the tegmen defects. A thin, flexible piece of Silastic sheeting (0.5 mm thickness) was then arranged across the modeled tegmen, marked, and cut to cover all of the proposed defect sites (Fig. 3). A notch was placed at the location of the middle meningeal artery. The shape of the Silastic sheet was highly irregular and variable from patient to patient. The Silastic sheet was then sterilized. Intraoperatively, the sterile Silastic sheet served as a template for creating the appropriately sized synthetic dural replacement graft (DuRepair; Medtronic, Dublin, Ireland), which was cut to match the Silastic template. The 3D-printed model also served as a nonsterile guide during the procedure for surgical reference.

Surgical Technique

A traditional temporal scalp flap was fashioned, and the skin and temporalis were reflected inferiorly. A middle fossa craniotomy was performed, and the temporal lobe was gently retracted. A Greenberg retractor was utilized to facilitate exposure of lateral skull base defects (Fig. 4). The nonsterile model was then reinspected to ensure all tegmen defects were visualized in situ. Calvarial bone grafts were harvested from the bone

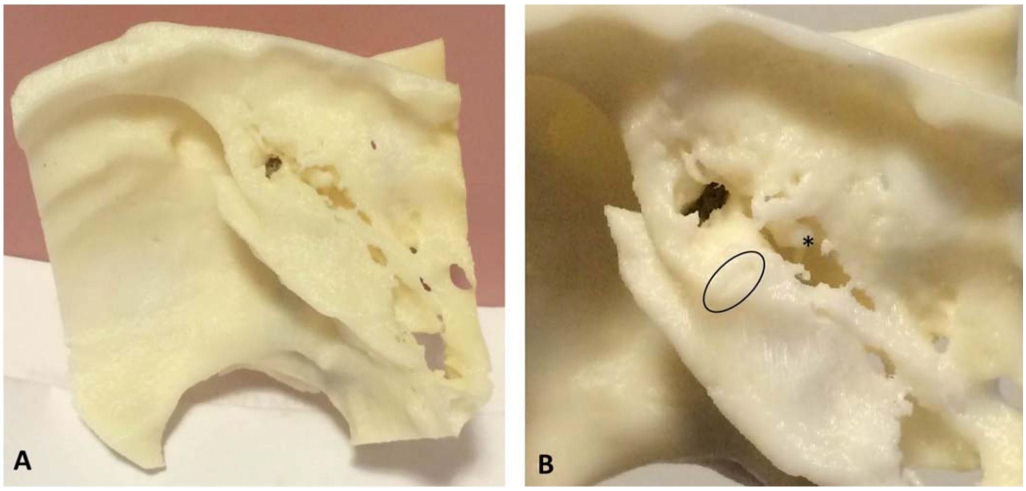

Fig. 2. (A) Low-power view of a three-dimensionally printed temporal bone model for patient 2. (B) High-power view of the same model demonstrating multiple tegmen mastoideum and tegmen tympani defects that are visible along with exposure of the ossicle heads (*) and dehiscence of the superior semicircular canal (oval). [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

flap and fashioned to span the largest defects. Once adequate exposure was obtained, the bone grafts were then secured with carbonated apatite bone cement (CraniOs; Synthes, West Chester, PA). The previously customized synthetic dural replacement graft was then placed into anatomic position along the floor of the middle cranial fossa to provide a watertight seal (Fig. 5). Tissue glue was placed, and the Greenberg retractor was relaxed as the temporal lobe was allowed to passively return. The craniotomy bone flap was replaced, and the wound was closed in a layered fashion. For some patients who had multiple small tegmen defects, the synthetic dural replacement graft was used in isolation.

RESULTS

Five patients underwent the middle cranial fossa approach to repair tegmen defects and spontaneous CSF leaks assisted by 3D-printed temporal bone models. 3D-printed temporal bone models were manufactured for each of these five patients. The resulting models compared favorably to the tegmen anatomy based upon imaging and intraoperative findings. Raw material cost was less than $5 per PLA model, $5 per ABS model, and $7 per Silastic sheet.

Three patients were female, and two patients were male. All five patients presented with CSF otorrhea after tympanostomy tube placement performed at outside institutions. The tympanostomy tubes were all removed preoperatively, and the tympanic membranes had healed spontaneously. One patient had a dehiscence of the superior semicircular canal, which was repaired along with his tegmen defects (patient 2). Patient characteristics and surgical outcomes are listed in Table I.

All five patients underwent successful repair of their tegmen defects without complications. The prefabricated dural repair grafts were easily placed and fit precisely onto the middle fossa floor without any additional modifications. All defects were covered as predicted by the 3D models. At their postoperative visits, all patients

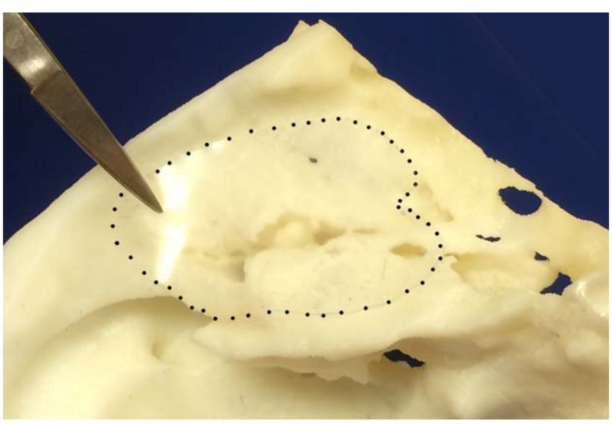

Fig. 3. Silastic sheeting customized to cover dehiscent and nearly dehiscent sites in the tegmen for patient 2. The clear Silastic sheeting is outlined. Note that foramen spinosum is not covered by the Silastic. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

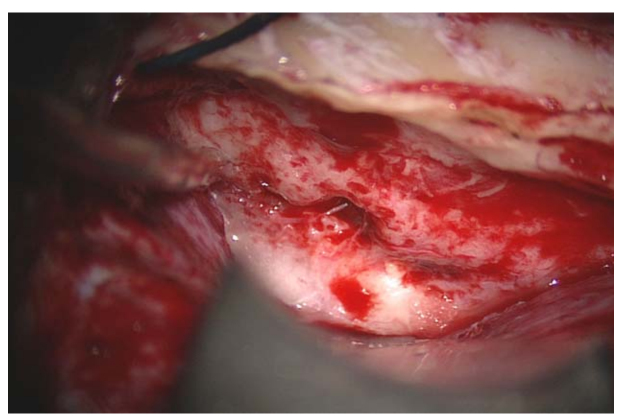

Fig. 4. Intraoperative view of multiple tegmen defects and nearly dehiscent sites in the right lateral skull base for patient 5. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

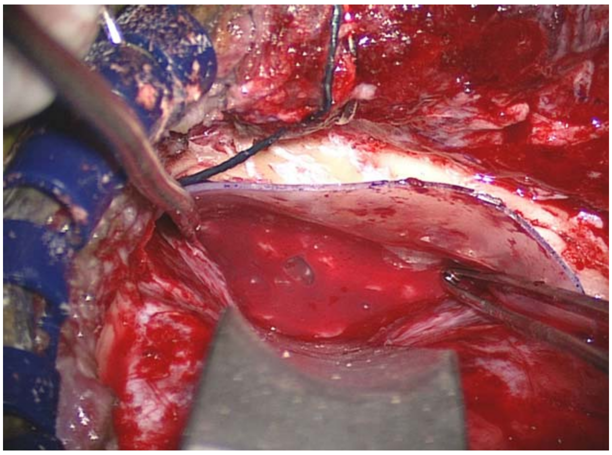

Fig. 5. The customized synthetic dural graft placed along the floor of the middle cranial fossa for patient 5. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

maintained resolution of their spontaneous CSF leaks, which was verified by the use of binocular otomicroscopy and formal tympanometry.

DISCUSSION

Reconstruction of defects in the middle fossa floor can be a challenging and frustrating procedure, and recurrence rates have been described as high as 28%.[9] One of the main challenges lies in obtaining adequate exposure to visualize all tegmen defects, especially anteromedial defects that lie near the geniculate ganglion. Use of 3D-printed temporal bone models aids in the visualization of all the tegmen defects and near-dehiscent sites preoperatively by providing a panoramic view that translates well to the view obtained in the operating room. Such models can be made from inexpensive materials and maintain high fidelity in demonstrating the tegmen anatomy. The 3D model of the lateral skull base provides the surgeon with a tangible display of all defects needing to be addressed, which improves surgical confidence that adequate exposure has been obtained.

Notably, although it is difficult to quantify this operative finding, the tegmen defects appeared to be slightly overestimated by the CT scan (and the subsequent CT-based 3D models). This is likely due to signal averaging of near-dehiscent regions. However, we strongly believe that repair of these near-dehiscent regions in addition to frankly dehiscent sites is critical to a durable repair and avoiding delayed failures.

Prefabricating a template for lateral skull base repair is a distinct advantage of the preoperative 3D temporal bone models. Silastic sheeting can be cut and fashioned to exactly match the compromised lateral skull base of the models, and can be subsequently sterilized and utilized intraoperatively. This helps reduce the degree of temporal lobe retraction, as the dural graft does not need to be directly sized to the tegmen intraoperatively. Once adequate exposure of the lateral skull base is obtained, the synthetic dural graft can be placed quickly and with a high level of confidence that all defects and nearly dehiscent sites are covered.

Currently, inexpensive materials available for 3D printing are difficult to sterilize due to their thermal properties. Our group is exploring options for materials that can be 3D printed with high fidelity and low cost and that can be reliably autoclaved. These materials should help to streamline the process of lateral skull base repair with 3D-printed models.

Our study has certain limitations. We believe that these repairs can be completed more quickly—with a shorter duration of brain retraction—with the use of 3D-printed temporal bone models, because the graft materials used for repair are customized before temporal lobe retraction occurs. However, we did not meticulously time the prefabricated repair in comparison to that of historical controls. In retrospect, the senior surgeon (H.A.A.) noticed a significant difference in time and ease of graft placement; however, we do not currently have timed data to validate this notion. Second, tegmen defects tend to be overestimated in the 3D models. This can lead to some uncertainty about whether a defect in the model is a true dehiscence or near-dehiscence. Our approach has been to cover all modeled defects, even if they ultimately represent a clinical near-dehiscence. We believe this may be beneficial in establishing a durable treatment benefit,

TABLE I.
Patient Characteristics.

Patient #	Gender	Age, yr	BMI, kg/m^2	Location of Tegmen Defects	Length of Follow-up, mo	CSF Leak Repaired?
1	F	61	34	Multiple small defects of tegmen mastoideum and tegmen tympani	4 mo	Yes
2	M	63	27	Large defect in the tegmen mastoideum and large defect in the tegmen tympani	7 mo	Yes
3	F	55	34	One small defect of the tegmen mastoideum and two small defects in the tegmen tympani	4 mo	Yes
4	F	48	29	Multiple small defects of the tegmen mastoideum and one large defect overlying the external auditory canal	4 mo	Yes
5	M	41	30	Multiple small defects of the tegmen mastoideum and one large defect of the tegmen tympani	6 mo	Yes

BMI = body mass index; CSF = cerebrospinal fluid; F = female; M = male.

as near-dehiscent sites may develop into frank dehiscence in the future. Notably, the Silastic sheet template in Figure 3 covers the frankly dehiscent and near-dehiscent sites, while avoiding the skull base foramina and groove for the middle meningeal artery and its branches along the inner surface of the lateral skull. Third, our follow-up was short, ranging from 4 to 7 months. Because we are reporting initial results on a novel technique, we do not yet have long-term data to validate a durable resolution of CSF leakage. As we continue to follow patients over time, we hope to obtain long-term data that validate this hypothesis.

A final concern is the accessibility of this technology to clinicians. In recent years, access to 3D printing technology has grown exponentially as multiple applications of this technology have been well described.[19] With improvements in low-cost machines, high-resolution desktop printers can now be purchased for around $1,000. The particular setup used in this modeling process cost $1,200. As printers become more affordable, we anticipate this technology will be accessible at most academic medical centers in the next 2 to 3 years either through the hospital or engineering departments. Furthermore, modeling software continues to improve, with many free software programs utilizing near-automated segmentation processes to simplify 3D modeling.

CONCLUSION

3D-printed temporal bone models of tegmen defects can serve as beneficial adjuncts during lateral skull base repair. Such models are inexpensive and can be made with most consumer or commercially available 3D printers. The models provide a panoramic preoperative view of all tegmen defects, increase surgeon confidence during and after the repair, and allow for preoperative custom templating of dural grafts without temporal lobe retraction.

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