Modular High-Fidelity Otolologic Surgical Simulator for the Training of Multiple Temporal Bone Procedures

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Abstract

Cadaveric temporal bones are the current gold standard for the training of otologic procedures; however, they have their limitations. Advances in software and manufacturing processes may provide an alternative solution. Last year, our team presented the preliminary design of a 3D printed stapedotomy simulator. Since this time, we have refined our model and collected user data to improve and verify the device’s utility. Using computer aided design and computer aided manufacturing, we have rapidly prototyped and modified our preliminary model. Otolaryngology residents from a single institution tested the simulator. Users were given a didactic lecture on stapedotomy procedures. They answered a questionnaire on the procedure. After, users assembled the model and performed a stapedotomy on the simulator. User performance was recorded, including the force applied at the footplate and number of instances contact was made with the facial nerve. After simulator use, users answered a questionnaire. From the collected and analyzed data, we have demonstrated that our system is an efficient training system for stapedotomy procedures, with the potential to be expanded to other procedures in the future.

Introduction

Clinically apparent otosclerosis affects approximately 0.4% of the population\(^7\), causing 1 – 5% of all cases of hearing loss\(^8\). This surgery is considered “one of the most technically challenging procedures performed by an otologist”\(^2\), and audiological outcomes are directly related to surgeon experience\(^6\). Unfortunately, residents today are exposed to few cases, possibly due to the steady decline in annual cases and increase in otolaryngologists.

Human cadaveric temporal bones can be used for training; however, they are limited by high costs, issues of storage, risks of pathogen transfer, toxic/carcinogenic risks of tissue preservatives, difficulties with recreation and repetition of similar surgical pathology from specimen to specimen, and the potential for conflict with religious beliefs\(^9\).

3D printing and widely available electronics offer new training opportunities. We have employed these technological advancements to create a low-cost and accurate stapedotomy simulator for otolaryngologist training.

Methods and Materials

• A 3D model of the middle ear was extracted from microCT scan of cadaveric temporal bone
• A housing system for the middle ear allowing for stapedotomy surgery simulation and multiple uses was designed in SolidWorks 2017
• A force sensitive resistor was incorporated beneath the stapes footplate and a conductive wire placed superior to the footplate for detection of forces and facial nerve contact during simulator use
• An Arduino was incorporated to receive and interpret data from the sensors and provides feedback to the user through production of a tone during nerve contact and digital display of the maximum force and current force detected during simulator use
• A pilot study of 14 users was performed to inquire on the simulator's efficacy

Figure 1. 3D model of middle ear cartridge and housing system for the simulator

Figure 2. 3D printers produced the CAD models. Left shows the assembled simulator along with the accompanying circuit box. Right image is the visualization users experience when operating on the simulator captured through an operating microscope as seen down the simulated EAC with the ossicular chain cartridge in place. The malleus manubrium is in view as well as the incus long process and stapes. Superior to the footplate is the simulated facial nerve, which will trigger a buzzer when contacted.

Results

The lengths of relevant ossicular anatomy in the model were 6.536mm for the incus long process, 4.926mm for the length of the incus short process, 4.096mm for the functional length of the incus long process, 3.354mm for the stapes height, and 5.009mm for the manubrium length. These values fall within the normal limits of ossicular anatomy found in the literature, making the model a suitable representation of middle ear. 3D printing could successfully reproduce the anatomy to scale at a low cost. The force sensitive resistor was calibrated to a logarithmic standard curve providing 0.888 variance for 5 tested resistors.

14 subjects were enrolled in the pilot study of the simulator. Participants were provided a didactic lecture overview of stapedotomy procedures and model use, asked to answer a questionnaire, operate on the simulator, and then answer a second questionnaire. Residents were tasked with disarticulation, superstructure downfracture, microdrill fenestration, and prosthesis placement. Results may be found in Table 1 and Chart 1.

Table 1. Summary of Stapedotomy Simulation questionnaire data for Medical Student, Junior Resident, and Senior Resident Cohorts. Questionnaire items were evaluated using a 0 (minimum) to 5 (maximum) scale or a binary Yes/No, unless otherwise noted. Cohort averages are listed for each questionnaire item. Relevant minimum and maximum values included in parenthesis.

<table>
<thead>
<tr>
<th>Questionnaire Item</th>
<th>Medical Students (n = 4)</th>
<th>Junior Residents (n = 7)</th>
<th>Senior Residents (n = 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stapedotomies Performed</td>
<td>0.00 (0)</td>
<td>0.14 (0-1)</td>
<td>4.00 (2.5-7)</td>
</tr>
<tr>
<td>Pre-Simulator Comfort Level</td>
<td>0.50 (0-2)</td>
<td>0.00 (0-0)</td>
<td>3.00 (2-4)</td>
</tr>
<tr>
<td>Post-Simulator Comfort Level</td>
<td>1.50 (0-5)</td>
<td>1.57 (0-3)</td>
<td>4.00 (4-4)</td>
</tr>
</tbody>
</table>

Simulator Design:

Overall Simulation Value | 5.00 (5-5) | 5.00 (5-5) | 5.00 (5-5) |
Accuracy of Stapedotomy Simulation | 4.00 (4-4) | 4.17 (4-5) | 4.00 (4-4) |
Helped Understand Anatomy? | 100% | 100% | 100% |
Useful Tool for Teaching? | 100% | 100% | 100% |
Recommend to Others? | 100% | 100% | 100% |

Procedure Simulation:

Maximum Force Applied (N) | 5.13 (4.60-5.70) | 5.66 (3.16-7.21) | 5.99 (5.61-6.35) |
Facial Nerve Contacts | 5.00 (0-9) | 2.29 (0-6) | 0.33 (0-1) |

Chart 1. Procedure Step Time. Average time to complete stapedotomy procedure steps for each cohort. Prosthesis placement data is not available for medical students as no subjects in this cohort completed the task.

Conclusions

We have developed a low-cost, high fidelity simulator for the training of stapedotomy procedures. Initial pilot data with residents demonstrates the utility of this training tool.

References

8. Pálfalvi I, Ochia O, Lidemann T, et al. A pilot study of 14 users was performed to inquire on the simulator’s efficacy.
The Predictive Utility of Temporal Bone Anatomy in Anticipating Morphology of the Ossicular Chain

Brandon Kamrava BS, Steven A. Zuniga MD, Pamela C. Roehm MD, PhD

Abstract

With our team’s previous development of a custom middle ear prosthesis, a prosthesis can be sized to the middle ear anatomy of a patient for ossiculoplasty. Proper sizing of our device requires knowledge of a patient’s ossicular morphology. Although clinical CT imaging resolution has advanced, the resolution is not sufficient for the precise measurement of the ossicular chain. We believe there may be anatomical correlations between temporal bone anatomy and the geometric morphology of the ossicular chain which would provide further insight for accurate preoperative prosthesis sizing. The literature was reviewed to define major landmarks identifiable on CT imaging. These landmarks were then used to limit to those whose position may be identified with limited variability between users. 5 cadaveric temporal bones were isolated, and both clinical high-resolution spiral CT and micro-CT scans were taken. Measurements were made between all landmarks using the spiral CT, leading to over 155 total measurements per bone. These measurements were then compared to the ossicular chain anatomy of each temporal bone as measured by micro-CT. Statistical analysis was then performed to observe any correlation between these measurements. This study has provided preliminary evidence of the predictive quality of temporal bone anatomy in reference to ossicular chain anatomy.

Introduction

Ossiculoplasty is a technically demanding procedure involving the repair of a disrupted ossicular chain. In cases with damage isolated to the incus and a preserved stapes superstructure, a partial ossicular reconstruction prosthesis (PORP) is commonly utilized for repair1. Prosthesis sizing dependent on the judgement of the surgical team at the time of the procedure. Improper determination of PORP length can lead to poor surgical outcomes1,2. Our team has developed a novel incus prosthesis which recreates the normal anatomy of ossicular chain with hopes of reproducing sound conduction better than conventional prostheses. We would like to assess if the morphology of the incus correlates with temporal bone anatomy as measured on HRCT, providing an opportunity to predict the incus’s anatomy through indirect measurements.

Methods and Materials

- 5 left cadaveric temporal bones were isolated and scanned with microCT and HRCT
  - microCT at 25 micron resolution and HRCT at 670 micron
  - 3D reconstruction of the ossicular chain created from microCT scans. Anatomical measurements were taken from these reconstructions (Figure 1)
  - HRCT scans were used to mark 18 critical landmarks and take 2 measurements from each bone (Table 1). The distance between each landmark was calculated, providing 155 total measurements.
  - The linear correlation between each landmark measurement and each morphological length of the incus was calculated. Coefficient of determination (R2) was determined for each value.
  - R2 were analyzed to find most correlated measurements and compare landmark measurements correlating to multiple incus morphologies.

Table 1: Landmark and Measurements Captured from Temporal Bone. 18 discrete and readily identifiable landmarks located in each temporal bone. In addition to these 18 landmarks, two landmarks, the base of the cochlea were found, one from the round window to the opposing end of the cochlea base and the other length perpendicular to the prior measurement.

Table: Comparison of Measurements Correlating with Incus Morphology. Multiple measurements found between landmarks of the temporal bone had a coefficient of determination (R2) greater than 0.9 in a linear correlation with incus measurements. Those which had a R2 greater than 0.9 for multiple incus measurements are listed below. The first two columns list the landmarks which measurements were taken between. An x indicates which incus measurement the landmark measurement had an R2 greater than 0.9.

Results

The R2 between incus morphology and temporal bone measurements was found, and for this study we limited our search to those greater than or equal to 0.9. These values can be found in Table 2. Articular surface height provided 12 R2 values greater than 0.80, 7 of which were greater than 0.90. Short process length provided 17 R2 values greater than 0.80, 6 of which were greater than 0.90. Long process length provided 30 R2 values greater than 0.80, 9 of which were greater than 0.90. Lenticular process length provided 6 R2 values greater than 0.80, 3 of which were greater than 0.90. Functional length provided 20 R2 values greater than 0.80, 4 of which were greater than 0.90. Long process angle provided 20 R2 values greater than 0.80, 5 of which were greater than 0.90.

Table 2: Linear Regression Comparing the 6 Measurements taken from the Incus on MicroCT to Temporal Bone Measurements. A linear regression was performed comparing the measurements found between major landmarks in the temporal bone and incus morphology. Only measurements with a coefficient of determination (R2) greater than 0.9 are included in this table. The first two columns reflect which two landmarks a measurement is being taken from.

Conclusions

Our team has developed a custom middle ear prosthesis requiring preoperative knowledge of incus morphology for proper implementation. Indirect measurement of the incus through use of landmarks in the temporal bone may provide an alternative solution to measuring incus morphology; however, more date is needed to clarify this possibility.

References