Fabrication of three-dimensional scan-to-print ear model for microtia reconstruction

Byoungjun Jeon, BS,a Chiwon Lee, PhD, b Myungjoon Kim, BS,a
Tae Hyun Choi, MD, PhD,c,* Sungwan Kim, PhD,b,d,**
and Sukwha Kim, MD, Phdc

a Interdisciplinary Program for Bioengineering, Seoul National University, Seoul, Korea
b Institute of Medical and Biological Engineering, Seoul National University, Seoul, Korea
c Department of Plastic and Reconstructive Surgery, Institute of Human Environment Interface Biology, College of Medicine, Seoul National University, Seoul, Korea
d Department of Biomedical Engineering, College of Medicine, Seoul National University, Seoul, Korea

ABSTRACT

Background: Microtia is a congenital deformity of the external ear that occurs in 1 of every 5000 births. Microtia reconstruction using traditional two-dimensional templates does not provide highly detailed ear shapes. Here, we describe the feasibility of using a three-dimensional (3D) ear model as a reference.

Materials and methods: Seven children aged from 11 to 16 (6 grade III and 1 grade II microtia) were recruited from Seoul National University Children’s Hospital, Korea. We generated 3D–computer-aided design models of each patient’s ear by performing 3D laser scanning for a mirror-transformed cast of their normal ear. The 3D-printed ear model was used in microtia reconstruction surgery following the Nagata technique, and its shape was compared with the casted ear model.

Results: One patient experienced irritation caused by accidently pouring resin into the external auditory meatus, and another had minor skin necrosis; both complications were successfully treated. The average percentage differences of the superior, inferior, anterior, posterior, and lateral views between the casted and 3D-printed ear models were 1.17%, 1.48%, 1.64%, 1.80%, and 5.44%, respectively (average: 2.31%), where the difference between the casted ear models and traditional two-dimensional templates were 16.03% in average.

Conclusions: Our results show that simple microtia reconstruction can be performed using 3D ear models. The 3D-printed ear models of each patient were consistent and accurately represented the thickness, depth, and height of the normal ear. The availability of the 3D-printed ear model in the operating room reduced the amount of unnecessary work during surgery.

© 2016 Elsevier Inc. All rights reserved.
Introduction

Microtia is a congenital external ear deformity that occurs in about 1 of every 5000 births. Most cases are unilateral but approximately 10% of deformities affect both external ears. Microtia and associated syndromes, for example, facial cleft, facial asymmetry, renal abnormalities, cardiac defects, microphthalmia, polydactyly, or vertebral anomalies, can decrease patients' quality of life mainly due to their low self-esteem.

Kristiansen et al. found the desire to have identical ears, perceiving their ear to look strange, frequent comments and/or questions from other people, the wish to wear sunglasses, and getting teased to be motivational factors for surgery. Also, there are reports that after ear reconstruction 91% of children reported improvements in self-confidence and that auricular reconstruction can improve the quality of life. Moreover, the success of microtia reconstruction is related to psychological postsurgical recovery of the patient. Therefore, microtia reconstructive surgery is desirable to reshape the ear deformity and reduce both physical and psychological problems.

General microtia reconstruction techniques involve the use of autologous costal cartilage, porous polyethylene (e.g., Medpor), and ear prostheses. Prosthetic reconstruction has a high success rate and good patient satisfaction, but its main drawback is that prostheses are not autologous tissue and therefore require ongoing expenses for maintenance visits and prosthesis replacement every 2-5 years. One problem with implant reconstruction using porous polyethylene (e.g., Medpor) is that it is a foreign body framework and sometimes requires secondary surgery for soft-tissue necrosis, as reported by Baluch et al.; in addition, it is a ready-made product that cannot replicate the patient's unique ear shape. Although these processes simplify ear reconstruction, the disadvantages stated above and a lack of training for newer surgical techniques mean that the most preferred method of microtia reconstruction among plastic surgeons is staged microtia repair using autologous costal cartilage.

Microtia reconstructive surgery using autologous costal cartilage is the most demanding surgical approach. The surgery includes harvesting a section or piece of the patient's rib cartilage and sculpting it into a newly shaped framework to repair the ear deformity. Two to three surgeries are usually performed over 12-24 months, depending on the patient's condition. Before harvesting the rib cartilage, surgeons copy the shape of the normal ear onto a two-dimensional (2D) transparent film by placing the film against the normal ear and tracing its anatomical landmarks. After harvesting the rib cartilage, surgeons use the film to guide sculpting. When carving the rib cartilage, surgeons experience some difficulties mimicking the three-dimensional (3D) ear shape because traditional microtia reconstructive surgery uses a 2D plane pattern although the ear is a 3D structure. Although the transparency of the film can project the mirror image of the normal ear and help surgeons sculpt the rib cartilage, it does not represent the unique 3D information of each patient, such as the height or thickness of the concha, helix, and antihelix. As a result, surgeons must keep checking and comparing the newly shaped framework with the normal ear. To compare the carved cartilage and patient's normal ear, surgeons have to bring the cartilage from the work station, which is located distant from the anesthetic patient's bed, and turn patient's head. During this additional step, operation time can be extended, and it also carries a slight risk of infection. To overcome these problems associated with this demanding ear reconstruction technique, 3D technologies are used.

The increase in 3D scanning and printing technologies has facilitated their use in microtia reconstructive surgery to help visualize the ear shape and sculpt the rib cartilage. A 3D template can be produced by scanning the normal ear cast, making a mirror image of the cast using computer-aided design (CAD) and printing out a 3D ear model for microtia reconstruction. This can result in more streamlined surgery and better outcome. In addition, the 3D-printed ear model can be shown to a patient and modified if necessary.

In the present study, we evaluated whether the use of 3D scan-to-print technique can provide detailed 3D information of the affected ear and enhance surgeon's intuition for ear cartilage framework by providing more objective 3D features when compared with the traditional 2D template-based ear reconstruction surgery.

Material and methods

Patients

A total of seven children (four females and three males) aged from 11 to 16, with six children grade III microtia and one child grade II microtia, were recruited from Seoul National University Children's Hospital in Seoul, Korea. To cast an ear model for patients, the institutional approval was obtained by the Institutional Review Board (IRB) of the Seoul National University College of Medicine and/or Seoul National University Hospital (IRB no. 1505-081-673). Every patient and their parents were told about the casting process with the possible risks and the benefits of how the casted ear model would be used for their microtia reconstructive surgery. After giving them a detailed information about intervention, permission from both patients and their parents were obtained by signing the informed consent. Casting of the patients' normal ears (four right and three left ears) was performed preoperatively, and all the ear reconstruction surgeries were performed.

Normal ear molding and casting

Normal ear molds were created instead of direct scanning because the children were too young to stay still during the 3D scanning process. Cotton plugs were used to protect the external auditory meatus. Surgical tape (Micropore, 3M) was used to cover the hairline around the normal ear to protect it from the alginate impression material. A 6 × 8 × 6-cm acryl frame with an open top and bottom was prepared to cast the patient's normal ear (Fig. 1).

Alginate impression material (Aroma fine plus 1 kg, GC Corporation, Japan) was mixed with tap water (8.4 g/20 mL) at room temperature for 20-30 s to create a mold of the normal ear. The mixed alginate was poured slowly into the acryl...
frame until the ear was covered with it. After 30-60 s, the acryl frame and the mold were separated from the patient’s ear while keeping the frame and the mold in contact. The mold was pushed inward (toward the top of the frame) to make room for the casting material.

A dental stone (Neo plum stone 1 kg, Mutsumi, Japan) mixed with tap water (100 g/24 mL) was filled in the frame containing the mold to fabricate a cast of the patient’s normal ear. Before filling the frame, less concentrated dental stone mixture was poured into the frame to prevent air bubbles from forming on the cast’s surface. After 2-3 h of drying, the mold and cast were separated from the frame. The mold was discarded, and the cast was used as the final material for 3D scanning.

3D scanning and printing

Three-dimensional scanning was performed with a NextEngine 3D laser scanner (3D Scanner HD, NextEngine) that generates an object’s 3D CAD model by capturing and registering 2D images and depth information based on the built-in image and laser sensors, respectively. The 3D CAD model is generated by applying the 3D scanner to the cast of the patient’s normal ear. To ensure sufficient resolution of the 3D CAD model, the 2D images and corresponding depth information of the cast were collected using an interval of 30°. After generating the 3D CAD model, mirror transformation was used to produce the 3D CAD model of the patient’s affected ear. For this purpose, we used the open source software MeshLab to process and edit the 3D model. Once the 3D model of the patient’s affected ear was obtained, we were able to print the model using a 3D printer (Edison, Rokit, Korea) at a resolution of 0.05 mm (Fig. 2).

Microtia reconstruction

Microtia reconstructive surgery was performed following the Nagata technique.\(^\text{10,12,16,17}\) After harvesting the patient’s rib cartilage, sculpting was performed using the 3D-printed ear model as a reference to fabricate a framework for microtia reconstruction (Fig. 3).

Evaluating 3D-printed ear model accuracy

To evaluate the percentage differences between the casted normal ear and 3D-printed ear model, a GNU image manipulation program (GIMP, The GIMP Team) was used to mirror transform one of the models. Next, the open source code of Mathematica was used to determine the percentage differences, and the merged images were collected and created. A digital camera was used to capture the five sides (superior, inferior, anterior, posterior, and lateral views) of each casted ear and 3D-printed model (Fig. 4 shows the lateral view). The black portion of the merged images shows the difference between the casted and 3D models. As a reference, lateral view of traditional 2D template consisting of x and y axis only was compared with casted ear model due to the absence of z axis in 2D coordinate.

Results

Patients and postoperative follow-up

The mean patient age was 13. Casts of each of the seven patients’ normal ears were produced. All the surgical procedures included a 3D-printed model as a reference of the affected
side. Although patients might have felt some discomfort when the resin was applied to their normal ear to create the mold, none of them had any problems (e.g., contact dermatitis or allergic reaction) from applying the alginate mixture, except for one case of irritation caused by accidently pouring a small amount of mixed alginate into the external auditory meatus. To minimize irritation, ear-nose-throat forceps were used to remove the solidified alginate inside the external auditory meatus. One patient also experienced minimal skin necrosis on the antihelix after microtia reconstruction, so we treated the necrosis by secondary intention. The other five patients did not have any complications.

Fig. 2  —  Affected side 3D ear model manufacturing process. After 3D scanning the cast, scanned image was reconstructed. The reconstructed image was then mirror transformed to generate 3D model of patient’s affected side ear. The generated 3D ear model was 3D printed. (Color version of figure is available online.)
Percentage differences between casted ear and 3D-printed ear model

Unlike 2D templates, the 3D printing outcomes of each patient were fairly consistent and accurate, representing normal ear symmetry (Fig. 4 and Table 1). The average percentage differences of the superior, inferior, anterior, posterior, and lateral views were 1.17%, 1.48%, 1.64%, 1.80%, and 5.44%, respectively, for an average 2.31% difference between the casted ear and 3D-printed ear models (Table 1).

Two-dimensional template and 3D ear model comparison

Traditional 2D template and casted ear model comparison gives different results as expected. Since there is no z-component in 2D coordinate system, percentage differences of the lateral view were the only possible outcome which was 16.03% (Table 2). Traditional 2D templates do not provide height information, which means that surgeons must continually check the patient’s normal ear while carving the rib cartilage. When using 3D ear model, however, surgeons do not need to keep track of the ear shape to acquire height information during sculpting (Fig. 3). Using a 3D ear model, it reduces unnecessary work during surgery. Compared to the 2D template, the 3D-printed ear model was a useful reference for visualizing the ear scaffold while sculpting valuable rib cartilage (Fig. 3).

Discussion

Major difficulty in microtia reconstruction is creating a 3D cartilage framework out of costal cartilage. There are several options for practicing cartilage framework designing suggested by Brent, Chen, Yamada et al which are summarized in Thadani’s article. However, practicing various methods with 2D template is still time-consuming for surgeon to locate parts of 3D ear in costal cartilage. The main issue is that the current surgical rehearsal or method for microtia reconstruction is to use 2D template when using harvested rib cartilage. This reference tool lacks the necessary information for reconstruction because it does not exactly represent the height, depth features, and mirror-imaged ear.

We used the promising methods of 3D scanning and printing to provide more detailed information for reconstruction. First, we tried to directly scan the patient’s normal ear with the 3D scanner. However, our patients were
too young to sit through the process, resulting in a low-quality 3D scanned image. To overcome the limitation, we created a mold of the normal ear and casted an ear model for 3D scanning (Fig. 1). There was no vibration or any other problem with scanning using the stationary casted model, which enabled us to rescan the model and reproduce a better, high-resolution 3D image. It also made it possible for the 3D scanner to obtain the information needed for mirror transforming and 3D printing. If faster 3D scanners were available other than the various types summarized by Murphy and Atala, it would have reduced the time needed to scan the casted model, making it possible to directly scan the patient’s ear.

The difference between the casted and 3D-printed ear models was only 2.31% (Table 1). In other words, 3D ear models were similar to the actual ear, regarding that the casted ear model is not different from the actual ear. This discrepancy may have been caused by our 3D scanner, which is not the best one available on the market. Still, the 3D-printed ear model looked exactly like the cast to the naked eye, except for the fact that it was mirror-imaged to be used as a reference tool during ear deformity reconstruction. A 2D model does not provide every unique detail of each patient’s ear, such as thickness, depth, or height information of the concha, helix, and antihelix. Conversely, the 3D model provided the information surgeons needed to sculpt the harvested rib cartilage (Figs. 3 and 4). Although the time to fabricate 3D-printed ear models is much longer than needed to trace anatomic landmarks on 2D film, this was not
problematic because 3D model preparation occurred before the day of surgery.

Another probable benefit of using the 3D model was the reduction in the amount of work during surgery. Carving rib cartilage usually takes place on a separately prepared table next to an anesthetized patient. Surgeons have to keep checking the normal ear when using the 2D template to guide rib cartilage sculpting. This involves turning the patient’s head and moving between the sculpting and patient tables.

The final results of microtia reconstruction are often evaluated by photogrammetry, but this was not possible in our study because secondary surgery is needed to complete the reconstruction (e.g., elevation and tragus reconstruction) which is required for skin to be completely and stably attached to framework for the actual ear shape to appear, and skin stabilization takes at least 6 mo after the first surgery of inserting the sculpted rib cartilage. As the purpose of this study was to determine whether a 3D model can be used as an intraoperative tool or reference during surgery, the photogrammetry evaluation will have to be performed in a separate study.

The applications of 3D technology are limitless; for e.g., it can be used for current and future techniques of ear reconstruction, such as creating ear prostheses, biocompatible ear scaffolds, and bioabsorbable scaffolds seeded with cartilage stem cells. Current ear prostheses are created by using a silicone mold of the ear but with 3D scanning and printing; fabrication can be simplified by directly scanning the ear and printing the prosthesis. Also, the shape of ready-made Medpor inserts can be customized by using 3D scanning and printing to create unique ear scaffolds matching each patient’s normal ear. The ultimate goal of regenerating an ear with autologous tissue can be achieved by 3D printing bioabsorbable materials like polycaprolactone with cartilage stem cells. The feasibility of using polycaprolactone scaffolds and cell-laden hydrogel as ear regeneration materials was demonstrated by Lee et al. In optimal in vitro experiments, 3D printing cell-laden materials with decellularized extracellular matrix can be used to mimic the microenvironment. Culturing cartilage stem cells and appropriately positioning an appropriate amount at the correct spot are the most difficult processes. If direct scanning, 3D printing of biocompatible or bioabsorbable scaffolds, and seeding cartilage stem cells can be performed, regenerating ear deformity with one’s own tissue is possible in the near future.

### Conclusions

The results of this clinical study demonstrate the usefulness of 3D scan-to-print technology for microtia reconstruction. We were able to fabricate the 3D-printed ear model and use it as a reference tool to simplify microtia reconstruction. The casted ear model was stable enough to allow the 3D scanner to acquire sufficient details of the ear shape. The thickness, depth, and height information of each patient’s 3D-printed ear models were consistently and accurately represented and helped surgeons sculpt the harvested rib cartilage and visualize the ear of the affected side. Moreover, the provided 3D-printed ear model reassured surgeons for cartilage framework when compared to using the traditional 2D template. The availability of the 3D-printed ear model in the operating room greatly benefits both patients and clinicians by reducing surgery time and effort.
Acknowledgment

Authors’ contributions: B.J., C.L., and M.K. contributed equally to this work as first authors. T.H.C. and S.K. contributed equally to this work as corresponding authors.

This study was supported by grant 05-2015-0010 from the Seoul National University Hospital Research Fund. This study was also approved by the Institutional Review Board of the Seoul National University College of Medicine/Seoul National University Hospital.

Disclosure

The authors have no financial disclosures and report no conflicts of interest with any of the companies or products mentioned in this article.

REFERENCES