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Conserving Cartilage In Microtia Repair: The Modular Component Assembly Approach To Rebuilding A Human Ear

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Abstract

Objectives—Current methods of microtia repair include carving an auricular framework from the costal synchondrosis. This requires considerable skill and may create a substantial donor site defect. Here, we present a modular component assembly (MCA) approach that minimizes the procedural difficulty and reduces the amount of cartilage to a single rib.

Study Design—Ex vivo study and survey

Methods—A single porcine rib was sectioned into multiple slices using a cartilage guillotine, cut into components outlined by 3D-printed templates, and assembled into an auricular scaffold. Electromechanical reshaping (EMR) was used to bend cartilage slices for creation of the helical rim. Chondrocyte viability was confirmed using confocal imaging. Ten surgeons reviewed the scaffold constructed with the MCA approach to evaluate aesthetics, relative stability, and clinical feasibility.

Results—An auricular framework with projection and curvature was fashioned from one rib. Surgeons found the MCA scaffold to meet minimal aesthetic and anatomic acceptability. When embedded under a covering, the region of the helix and anti-helix of the scaffold scored significantly higher on the assessment survey than that of an embedded alloplast implant (t-value=0.01). Otherwise, no difference was found between the embedded MCA and alloplast implants (t-value >0.05). EMR treated cartilage was found to be viable.

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Level of Evidence: N/A

Conclusion—This study demonstrates that one rib can be used to create an aesthetic and durable framework for microtia repair. Precise assembly and the ability to obtain thin, uniform slices of cartilage were essential. This cartilage-sparing MCA approach may be an alternative to classic techniques.

Keywords

Microtia; auricular repair; costal cartilage modular component assembly; TPF; cartilage

Introduction

Microtia, an abnormality in which the external ear anatomy is either underdeveloped or absent, occurs in approximately 1 in every 10,000 births.¹ Autogenous auricular reconstruction remains the preferred method for microtia reconstruction, but continues to be one of the most difficult procedures in reconstructive surgery. Contemporary microtia repair using autologous tissue was first pioneered by Tanzer (1971) and involves multi-staged surgical techniques that require the harvest of a substantial amount of rib.² Subsequent iterations of this method were developed by Brent (1980), Park (1991), Nagata (1993), and Firmin (1993), which have optimized and reduced the number of stages to derive the current standard of microtia repair.^{3–12}

Recent efforts by various groups have attempted to advance upon these techniques to improve aesthetic outcomes and to simplify the process by further decreasing the total number of stages needed. A study published recently by Kasrai et. al. demonstrates a modified version of the Nagata technique characterized by adding ear projection early on in the reconstructive period with the use of a projection block.¹³ This allows projection to be achieved early on in the reconstructive process, but also requires additional cartilage. Even more recently, Siegert et. al. (July 2015) investigates a novel method for improved elevation and stabilization of the pinna in autologous microtia repair using a new periosteal flap technique.¹⁴

Regardless of technique, however, all contemporary approaches require the harvest of multiple ribs from the synchondrosis and exceptional skill with carving. A recent study by Wallace et. al. refutes a much-debated topic regarding the long-term effects of donor site morbidity after rib harvest for microtia reconstruction. In this study, it was found that patients sustained significant localized skeletal deformations quantified by three-dimensional CT imaging regardless of meticulous donor-site management.¹⁵ This suggests the need for a revised microtia reconstruction technique that requires less rib. Alloplastic implants provide an alternative with no donor site morbidity, however, they are not without complications, such as infection and extrusion. In a recent study by Constantine et. al., polyethylene implants were found to achieve a better cosmetic outcome in terms of ear definition, shape, and size, but with a higher risk for infection and extrusion.¹⁶ Comprehensive tissue engineering approaches are promising, but broad clinical use for microtia is still likely at least a decade away.¹⁷ Hence, there remains a need for a simplified method to reconstruct the auricular framework using native tissue with less donor site morbidity and acceptable cosmetic results.

We describe an experimental approach to auricular scaffold reconstruction in which precisely cut components fabricated from thin slabs of cartilage are assembled into a three-dimensional, projected auricular framework. This modular component assembly (MCA) approach can potentially be used to reconstruct an ear using a single rib, which reduces waste of autologous cartilage tissue. In addition, this method aims to reduce reliance upon surgical technical skill, standardize framework reconstruction, and produce consistent results. The described approach utilizes two key components: 1) the use of a cartilage guillotine to section cartilage into precise, user-defined thicknesses^{18, 19}, and 2) electromechanical reshaping (EMR) to create the required curvature of the cartilage tissue via an in-situ redox chemistry based mechanism.^{20–30} Using these two technologies, components of the framework are created and suture-assembled into an auricular framework using a single rib. We then evaluated the feasibility of MCA scaffolds using a focus group of surgeons familiar with microtia surgery.

Materials and Methods

Tissue Harvest and Sectioning

Porcine ribs were obtained from a local packinghouse and the cartilaginous fifth rib was harvested. A cartilage guillotine was used to precisely section the rib into multiple slices of 1mm and 2mm thickness (Figure 1A–D).^{18,19} Following sectioning, the slices were placed directly in phosphate buffered saline (PBS) for hydration. For reconstruction of the auricular scaffold, one 2 mm thick section and at least seven 1 mm thick slices, of variable shapes and lengths, were required. One thick peripheral segment of residual cartilage was used for construction of the anti-tragus, as detailed below.

Electromechanical Reshaping

After 15 minutes of immersion in PBS, the 2 mm thick section was curved using EMR to create the superior portion of the 2-part helical rim. EMR is a non-thermal reshaping technology that creates in situ redox changes in tissue leading to local stress relaxation and is described in detail in the literature.^{19–29} The reshaping process was performed by first securing the 2 mm cartilage specimen to a cylindrical cork mandrel (diameter=15 cm) using needles. The mandrel provided a degree of overcorrection to compensate for shape memory effects (Figure 1E–G). Thereafter, platinum coated anode and cathode electrodes (F-E2M-48, Grass Technologies, West Warwick, RI) were spaced evenly 2 mm apart and inserted into the specimen spanning the entire circumference of the mandrel. The electrodes were connected to terminals of a DC power supply (Model PPS-2322, Amrel, Arcadia, CA, USA), and dosimetry of 5 V for 3 minutes was applied.^{20–30} The electrodes were then removed, and the tissue and mandrel (with needles in place) were placed in PBS for 15 minutes to allow for rehydration and stabilization of shape. No other cartilage segments were reshaped using EMR.

Confocal Microscopy and Viability Analysis

Chondrocyte viability of the cartilage specimens after EMR was assessed using the Live/Dead viability assay (Molecular probes, Eugene, OR, USA) in conjunction with confocal microscopy as described previously.^{24–34} Confocal images were obtained after the specimen

was removed from the mandrel and stored in 0.9% 0.154 M saline solution for 1 hour. The number of live cells in the regions in contact with electrodes was compared to the number of live cells in the regions not in contact with electrodes.³⁵

Construction of the 3D Printed Templates

To simplify the scaffold construction process, plastic templates for each scaffold component were designed using computer-aided design software (Solid Works, Waltham, MA), and constructed out of ABS plastic using 3D printing technology (Flashforge Creator, Jinhua, Zhejiang, China) (Figure 2). The 3-D template serves two roles. First and foremost, it allows for standardization and easy replication of the MCA method. Templates were used as a guide to measure and cut the cartilage slices into appropriate shapes and for suture assembly. Furthermore, the 3-D printed templates aided in suture assembly, as they are designed with holes in them so that the cartilage can be secured to one another with a needle during suture assembly. Secondly, the 3-D template can be patient specific as microtia is usually unilateral. Thus the surgeon can use the measurements of patient's opposite ear as guide for the 3-D printed template.

Cartilage Scaffold Assembly

Figure 3 is a schematic illustrating the sequential MCA approach used to construct the cartilage scaffold. First, the main base was created using three 1 mm thick slices of cartilage that were cut into shapes using templates and secured together with 6-0 nylon suture (Ethicon Inc., Somerville, NJ) (Figure 3, step 1). Note: this step requires some improvisation by the surgeon, as costal cartilage segments will vary in size from patient to patient. Thus, it may be necessary for the surgeon to suture two pieces of cartilage together to make one section of the base, as demonstrated in Figure 3, Alternative Step 1. Next, the conchal bowl was created using two 1mm slices of cartilage that were sutured together perpendicularly (Figure 3, step 2). The entire conchal bowl was then sutured perpendicularly to the main base to create 3D projection (Figure 3, step 3). The helical rim was constructed by suturing a 1mm thick slice of cartilage (inferior portion of rim) to the EMR-reshaped 2 mm thick slice of cartilage (superior portion of rim). Then, the entire helix was sutured perpendicularly to the main base, and the superior most region was sutured to the cartilage foundation to create the cymba concha (Figure 3, step 4). The antihelix, including the antihelical crura, was created using two 1mm thick pieces that were cut in the shapes of the templates, overlaid in a stacking fashion on top of one another to achieve desired thickness, and secured to the main base with sutures (Figure 3, step 5). A thick residual segment of cartilage intended for the anti-tragus was secured to the inferior most portion of the scaffold using either Derma Bond (Ethicon US, LLC, Cincinnati, OH) or suture (Figure 3, step 6). Finally, a scalpel was used to smooth any sharp edges and to make any subtle final adjustments.

An iterative approach was used to create ten auricular cartilage frameworks and resulted in the final assembly process described above, taking on average 1 to 2 hours to complete each ear.

Assessment of Scaffold Morphology

Six boarded facial plastic surgeons, three pediatric otolaryngologists, and one plastic surgeon were surveyed to evaluate the aesthetics, relative mechanical stability, and clinical feasibility of the final scaffold assembly. Each surgeon was asked to inspect three different frameworks (Ear A, B, and C) (Figure 4 A–C). Ear A (Figure 4A) consisted of a naked cartilage scaffold. Ear B (Figure 4B) consisted of a cartilage scaffold covered by a thin layer (approximately 2mm in thickness) of modeling clay (Polyform Products Company, Elk Grove Village, IL) to simulate a soft tissue layer (e.g., temporal-parietal fascia) (Figure 4C).³⁶ Ear C (Figure 4C) was a porous polyethylene implant (MedPor® implant, Stryker, Kalamazoo, MI) also covered with a 2 mm clay layer. Besides Ear A, the surgeons were blind with respect to which clay-covered ear contained either the autologous cartilage implant or the MedPor® implant. For each ear, surgeons subjectively rated the aesthetic acceptability of specific outer auricular structures as classified by Tolleth et. al.³⁷ For Ear A, mechanical stability was also surveyed by having the surgeons palpate the manipulate the scaffold. Furthermore, surgeons were asked general questions regarding the MCA method to assess clinical adoption feasibility and to compare it to conventional methods (ie: Tanzer and Brent methods). Responses were graded using a 5-point Likert scale.

Results

Cartilage Scaffold

A projected, anatomically correct, and sturdy cartilaginous scaffold was created using only cartilage obtained from the 5th porcine rib (ranging 8–12 cm long by 1–2 cm wide). Figure 5 demonstrates scaffold projection. The scaffold constructed was 6.8 cm long, 3.0 cm wide, and 10 mg in weight, which is consistent with average pinna sizes.³⁸

Confocal Microscopy and Tissue Viability Following EMR

Confocal imaging of EMR reshaped regions demonstrated a 2 mm diameter region of tissue injury surrounding either anode or cathode. This is consistent with previous studies.²²

Assessment of Aesthetic Acceptability, Sturdiness, and Feasibility for Clinical Use

Ear A (cartilage framework without clay cover) met minimum acceptability requirements, and all sub-structures ratings ranged between 3.3 and 4.8. The stability and sturdiness of the auricular framework was deemed sufficiently stable for potential clinical use, with rating of 4.6 and 4.2, respectively. Ear B (cartilage scaffold embedded under a clay cover) met minimum morphologic acceptability requirements, with ratings of 3.5 and higher. In addition, Ear B was rated better than or equal to Ear C (alloplast implant embedded under clay mold) with regards to morphologic acceptability. Specifically, the only auricular structure on Ear B that was scored significantly higher than Ear C was the helix/anti-helix (t-value=0.01). There was no statistical difference found between Ear B and C for other surface features (t-value>0.05).

Collectively, the entire MCA process: 1) compared favorably with conventional methods (3.9 out of 5); 2) created a scaffold resembling a human ear (4.3 out of 5); and 3) was found

to be suitable for both pediatric microtia repair and adult auricular reconstruction, 4.3 and 4.2 respectively.

Discussion

A sculpted, costal cartilage framework remains the standard of care for microtia correction and all reported methods to achieve this goal require the harvest of multiple ribs. These methods have a steep learning curve and can be associated with donor site and recipient morbidity.³⁹ We believe the MCA approach could address the shortcomings of carving-based approaches and is a potential paradigm shift in microtia repair. In actuality, the amount of elastic cartilage in a native ear is usually much *less* than the amount of cartilage that must be harvested for microtia repair using the synchondrosis technique, resulting in tissue waste. In contrast, the MCA approach uses cartilage much more efficiently, requiring only 1 rib. In the MCA approach, the auricular scaffold is assembled from uniformly sectioned cartilage slices whose shape is specified by templates that serve as a guide for 3D assembly. The individual components, all crafted from 1 or 2 mm thick rib slices, are carefully designed such that construction of an auricular scaffold follows a systematic, easy-to-follow, and standardized approach.^{40–41} Our findings suggest that this approach produces an acceptable framework, though refinement of the specific approach will be needed.

Crafting the modular components for framework assembly was achieved through the precise sectioning of costal cartilage and re-shaping the helical component. The cutting device used herein sections a single rib into uniform slices that are 1–2 mm thick. This device has already been used in rhinoplasty surgery and is sold commercially.^{18, 19} It does require some practice, typically using porcine rib, to achieve a level of comfort and familiarity. In contrast to the cartilage cutter, EMR is still an experimental technology where electrodes connected to a simple DC power supply are inserted into tissue to create in situ redox reactions that lead to accelerated stress relaxation and shape change.^{20–30} The technique is straightforward, time efficient, and easy to sterilize. It is cost effective, as it can be accomplished using just AA batteries and low cost electrodes. Also, tissue injury is highly localized and comparable to gentle morselization.^{20–30}

The MCA approach demonstrated here represents a starting point. Future iterations will amount to different tessellation patterns and better framework designs. Also, a substantial amount of suturing is required for the MCA approach compared to conventional methods, and it is estimated that the entire protocol would take about one hour or less for an experienced surgeon to complete. In contrast to a carved synchondrosis, MCA creates a scaffold that is thinner, pliable, and potentially more anatomically accurate. In this same light, a thinner graft created via the MCA method may be more susceptible to deformation by skin contracture than grafts made via traditional carving methods. However, the use of a temporoparietal fascial flap (TPFF) may eliminate this possible complication. TPFF with full thickness skin grafts (FTSG) are now more widely used due to the introduction of Medpor® implants. Current literature supports use of TPFFs covered by FTSGs in both alloplast and autogenous microtia repair.^{42–47}

The focus group evaluation determined that at this point, the MCA scaffold achieves relative aesthetic acceptability, appropriate size feasibility for clinical use, and compares favorably to a widely used alloplast implants. It is important to note that the tragus was not present in either model, as this structure is often not part of the cartilage scaffold and is instead added after the microtia repair process is complete in most conventional techniques.

The use of clay to emulate a skin-soft tissue layer does merit discussion. The thickness of this layer over either the cartilage scaffold or the Medpor® scaffold is biased and limited by the author's skill and subjectivity (in this case author JRG), especially in the lobule, which was created de novo for each ear. Although it was attempted to maintain a uniform 2 mm thick layer, it was difficult to control thickness over the entire surface. Regardless, 2 mm is a practical thickness to work with when using clay and compares favorably to the measurements of the skin thickness over the human ear.³¹ Alternate approaches to simulate the skin soft tissue layer are limited. A silicone scaffold covering was considered. However, immersing the scaffold into the polymer did not allow for control over auricular definition or lobule creation because using a liquid polymer that required a set cure time resulted in variable covering thickness. Small animal models also fail to adequately represent soft tissue coverings due to form factor issues, and large animals have substantially thicker skin layers and are prohibitively expensive. Given the preliminary nature of this study and the focus on introducing the MCA approach, clay was the most practical approach to demonstrate how the scaffold would appear beneath skin and soft tissue. Silicone vacuum modalities could instead be used for microtia training purposes using the MCA method to better emulate the final ear project and assess progress made by surgeons in training and to better assess feasibility of clinical adoption.

The survey required in-person meetings with one investigator (JRG), which may have led to score inflation.⁴⁸ This approach, however, was deemed integral in order to adequately define the project's objectives and details of the protocol, which could not be accomplished otherwise. The focus group population was a limited sample (n=10), and all participants were engaged in resident education to some degree.

To our knowledge, using the MCA approach to reduce the amount of rib needed for scaffold construction is a novel technique.⁴⁹ Obviously, refinement is necessary and different patterns of surface tessellation could be devised to improve both aesthetic and structural outcomes. For example, additional methods for cartilage manipulation could be incorporated to achieve even more delicate contours, such as recent methods developed by Lee et. al. that use skin punch biopsy instruments to sculpt cartilage for microtia repair.⁵⁰ Furthermore, a more objective means of measuring scaffold stability and durability will be needed, such as using a finite element analysis, as previously studied in our lab with nasal cartilage. Moreover, clinical adoption will be necessary but difficult, as there is no sufficient animal model for microtia repair, leaving incremental clinical adoption a feasible next step after method improvement. However, the first steps are presented herein. Our lab is already focused on developing improvements through further ex vivo studies and cadaveric models. Porcine tissue used here differs from its human counterpart, but the disparity is modest. In humans, the 7th rib provides the most amount of costal cartilage, and would be sufficient to construct an MCA auricular scaffold.⁵¹

Overall, as stated previously, there is a need for an adequate animal model for microtia repair. Thus, it may be difficult to transition the MCA approach to clinical use. However, incremental adoption may be feasible and pilot use of elements of the MCA approach in conventional cases may be explored, starting with helical rim construction.

Conclusion

This study establishes a modular component assembly approach for the construction of an auricular scaffold for microtia repair that reduces cartilage and minimizes procedural difficulty. MCA creates a cartilage scaffold from a single rib that is sliced into uniform segments, cut into shapes according to templates, and sutured together. The auricular framework constructed from this approach was deemed to be aesthetically acceptable and clinically feasible by a focus group. We believe the MCA approach is a starting point for a new cartilage conserving and standardized microtia repair methods.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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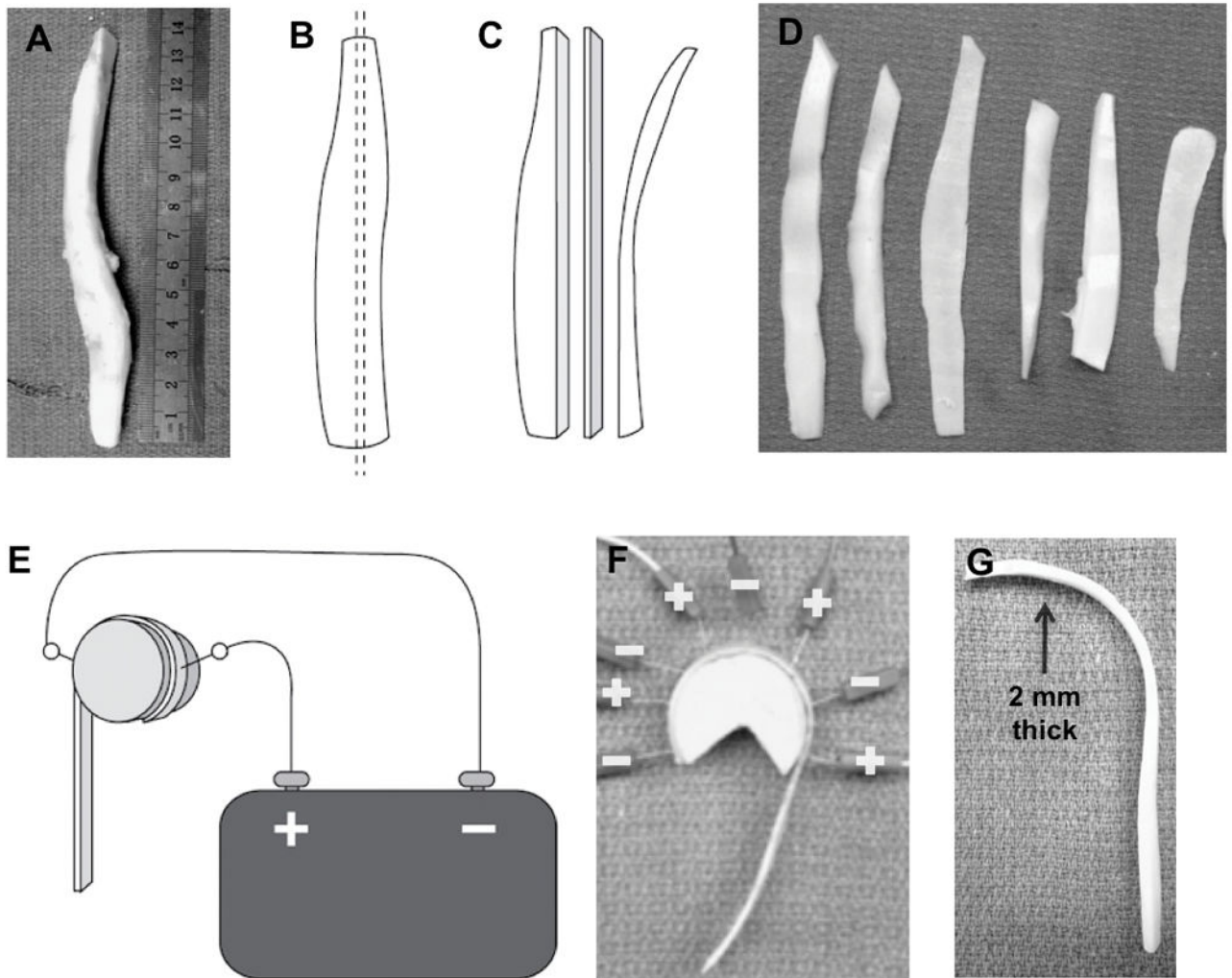


Figure 1. Diagram of experimental rib harvest and experimental design

A) Fifth porcine costal cartilage after removal of surrounding soft tissue. B–D) Several slices, measuring 1–2mm in thickness, obtained from the cartilaginous rib. E–G) A 2mm thick slice curved for the helical rim using EMR. A cylindrical cork jig was used to maintain the cartilage in a curved position during EMR.

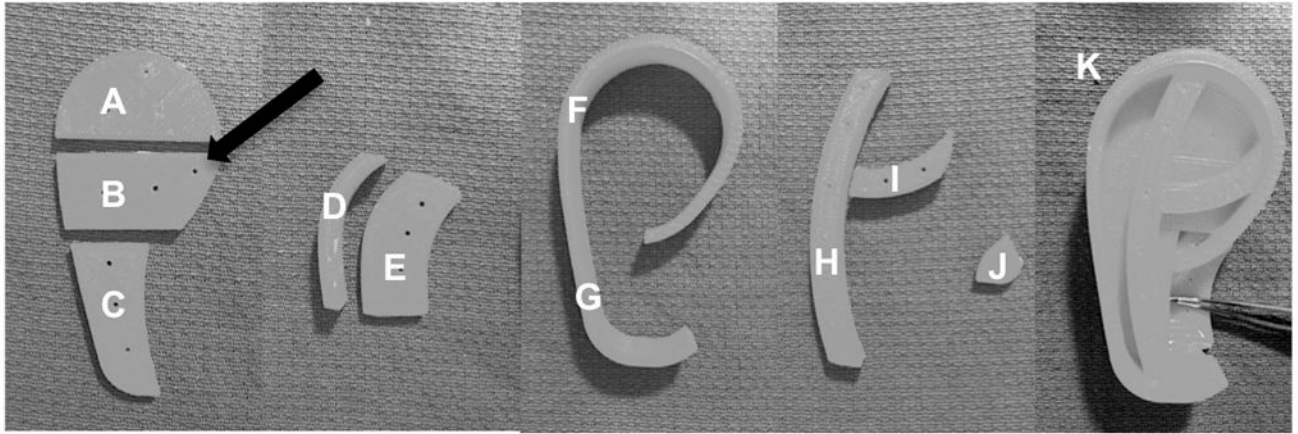


Figure 2. 3D printed plastic templates aided in cartilage shaping and assembly

Three 1 mm thick slices of cartilage were cut into shape with the templates to create the main base (A, B, C). Next, the conchal bowl was created using two 1mm slices of cartilage (D and E) that were sutured together perpendicularly, and then sutured to the main base to create the 3D projection of the concha bowl. The helical rim was assembled using one 2mm thick slices of cartilage (F) and one 1mm thick slice (G), and was sutured perpendicularly to the foundation cartilage. The helix, including the helical crura, was created using two pieces of cartilage overlaid on top of the foundation cartilage and secured with sutures (H and I). A thick residual segment of cartilage (J) was secured to the inferior most portion of the scaffold to form the anti-tragus. K) A 3D printed scaffold was created to aid in reproducibility and better understanding of the assembly process.

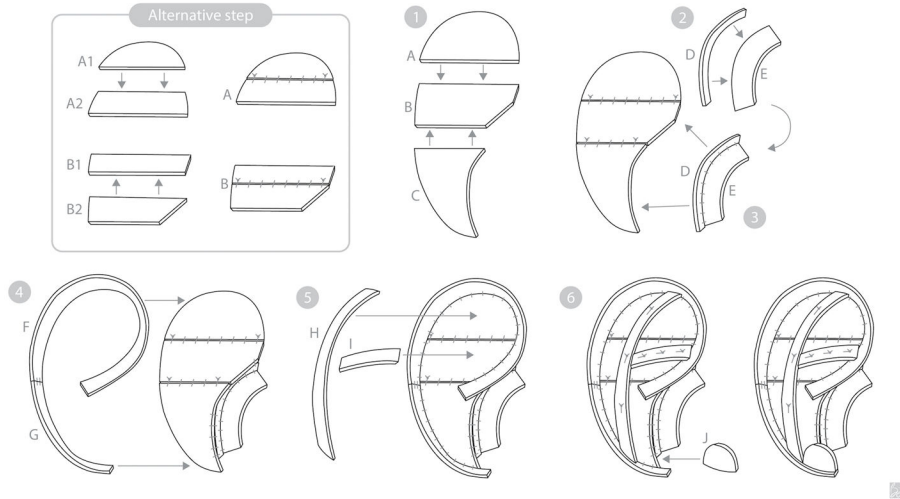


Figure 3. Diagram of the cartilage scaffold assembly

The scaffold was created in a step-wise approach using the 3D printed plastic jigs as a guide. Plastic templates were designed and three-dimensionally printed to streamline the cartilage scaffold construction process. Cartilage pieces were cut into their respective shapes and sutured together. The making of the scaffold base, requires some improvisation, as costal cartilage segments will vary in size from patient to patient. Thus, it may be necessary for the surgeon to suture two pieces of cartilage together to make one section of the base, as demonstrated in Alternative Step 1.

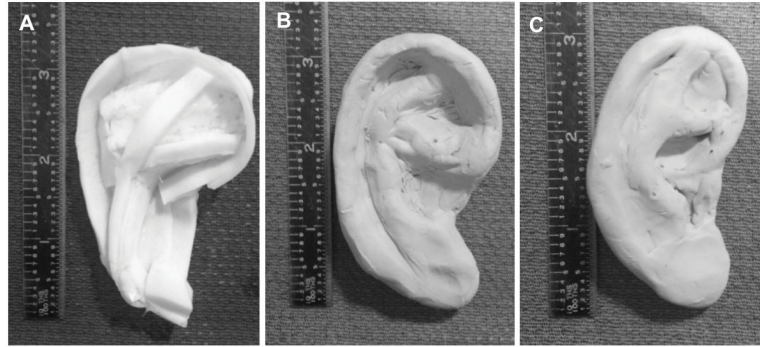


Figure 4. Specimens evaluated by surgeons to determine scaffold and MCA approach feasibility and acceptability

- A) Autologous auricular scaffold made from the modular component assembly method (Ear A). B) Modular component assembly autologous scaffold covered by a clay mold (Ear B). C) Alloplast scaffold covered by a clay mold (Ear C).

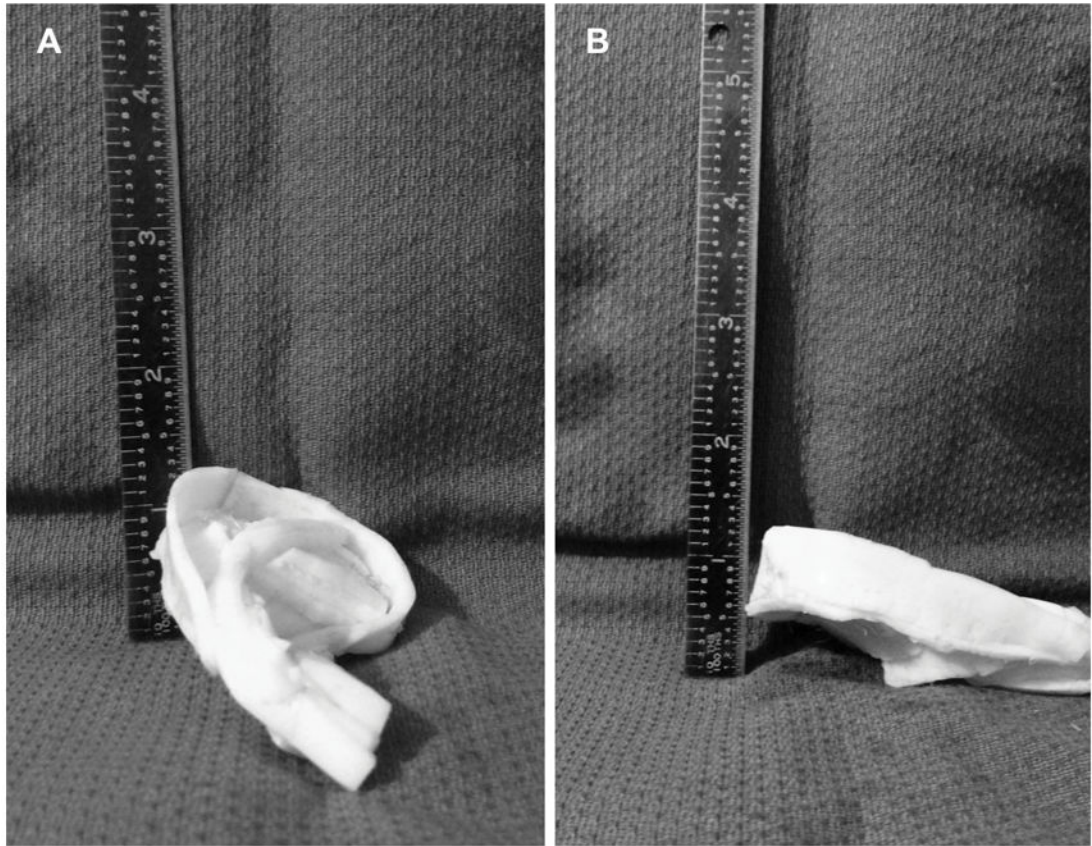


Figure 5. Scaffold Projection
Lateral view of the scaffold demonstrating adequate lateral projection.