Modular Component Assembly Approach to Microtia Reconstruction

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BACKGROUND  Current methods of microtia reconstruction include carving an auricular framework from the costal synchondrosis. This requires considerable skill and may create a substantial defect at the donor site.

OBJECTIVE  To present a modular component assembly (MCA) approach that minimizes the procedural difficulty with microtia repair and reduces the amount of cartilage to a single rib.

DESIGN, SETTING, AND PARTICIPANTS  Ex vivo study and survey. A single porcine rib was sectioned into multiple slices using a cartilage guillotine, cut into components outlined by 3-dimensional printed templates, and assembled into an auricular scaffold. Electromechanical reshaping 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, stability, and clinical feasibility. The study was conducted from June 5 to December 18, 2014.

MAIN OUTCOMES AND MEASURES  The primary outcome was creation of a modular component assembly method that decreases the total amount of rib needed for scaffold construction, as well as overall scaffold acceptability. The surgeons provided their assessments through a Likert-scale survey, with responses ranging from 1 (disagree with the statement) to 5 (agree with the statement). Thus, a higher score represents that the surgeon agrees that the scaffold is structurally and aesthetically acceptable and feasible.

RESULTS  An auricular framework with projection and curvature was fashioned from 1 rib. The 10 surgeons who participated in the survey indicated that the MCA scaffold would meet minimal aesthetic and anatomic acceptability. When embedded under a covering, the region of the helix and antihelix of the scaffold scored significantly higher on the assessment survey than that of an embedded alloplast implant (mean [SD], 4.6 [0.97] vs 3.5 [1.27]; P = .007). Otherwise, no significant difference was found between the embedded MCA and alloplast implants (4.42 [0.48] vs 3.87 [0.41]; P = .13). Cartilage prepared with electromechanical reshaping was viable.

CONCLUSIONS AND RELEVANCE  This study demonstrates that 1 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.

LEVEL OF EVIDENCE  NA.
Microtia, an abnormality in which the external ear anatomy is either underdeveloped or absent, occurs in approximately 1 in every 10,000 births. 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 pioneered by Tanzer and involves multistaged surgical techniques that require the harvest of a substantial amount of rib. Subsequent iterations of this method were developed by Brent, Park et al, Nagata, and Firmin, which have optimized and reduced the number of stages to derive the current standard of microtia repair.

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

Regardless of technique, all contemporary approaches require the harvest of multiple ribs from the synchondrosis and exceptional skill with carving. A recent study by Wallace et al refuted a much-debated topic regarding the long-term effects of donor site morbidity after rib harvest for microtia reconstruction. In that study, patients sustained significant localized skeletal deformations quantified by 3-dimensional (3D) computed tomographic imaging regardless of meticulous donor-site management. This finding 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. Comprehensive tissue-engineering approaches are promising, but broad clinical use for microtia is still at least a decade away. 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 3D, 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, the MCA method aims to reduce reliance on surgical technical skill, standardize framework reconstruction, and produce consistent results. The approach described here includes 2 key components: (1) use of a cartilage guillotine to section cartilage into precise, user-defined thicknesses and (2) electromechanical reshaping (EMR) to create the required curvature of the cartilage tissue via an in situ, redox chemistry-based mechanism. With the use of these 2 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.

Methods

Tissue Harvest and Sectioning

Based on the University of California–Irvine institutional review board requirements for nonhuman subject research determination, the present study did not require institutional review board approval. The present study used porcine cartilage for the production of the ear cartilage scaffold and the focus group of facial plastic surgeons was asked for an assessment of the final product. Thus, the present study was determined not to require institutional review board approval. The facial plastic surgeons provided oral consent for their participation in the study; they received no financial compensation. 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 1- and 2-mm thickness (Figure 1A-C). Following sectioning, the slices were placed directly in phosphate-buffered saline for hydration. For reconstruction of the auricular scaffold, one 2-mm-thick slice 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 antitragus, as detailed below.

Electromechanical Reshaping

After 15 minutes of immersion in phosphate-buffered saline, the 2-mm-thick section was curved using EMR to create the superior portion of the 2-part helical rim. Electromechanical reshaping is a nonthermal reshaping technology that creates in situ redox changes in tissue leading to local stress relaxation; it has been described in detail. The reshaping process was performed by first securing the 2-mm-thick cartilage specimen to a cylindrical cork mandrel (15-cm diameter) with the use of needles. The mandrel provided a degree of overcorrection to compensate for shape memory effects (Figure 1D-F). Thereafter, platinum-coated anode and cathode electrodes (F-E2M-48; Grass Technologies) 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 direct-current power supply (PPS-2322; Amrel), and dosimetry of 5 V for 3 minutes was applied. The electrodes were then removed, and the tissue and mandrel (with needles in place) were placed in phosphate-buffered saline 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 a viability assay (Live/Dead; Molecular Probes) in conjunction with confocal microscopy as
Confocal images were obtained after the specimen was removed from the mandrel and stored in 0.9% 0.154M saline solution for 1 hour. The number of live cells in the regions in contact with electrodes was compared with the number of live cells in the regions not in contact with electrodes.

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 (3D CAD Software, 2013 version; SolidWorks) and constructed with acrylonitrile butadiene styrene plastic using 3D printing technology (Flashforge Creator) (Figure 2). Templates were used as guides to cut the cartilage slices into appropriate shapes and for suture assembly.

Cartilage Scaffold Assembly
Figure 3 is a schematic illustrating the sequential MCA approach used to construct the cartilage scaffold. In step 1, the main base was created using three 1-mm-thick slices of cartilage that were cut into shapes according to templates and secured together with 6-0 nylon suture (Ethicon Inc). In step 2, the conchal bowl was created using two 1-mm-thick slices of cartilage that were sutured together perpendicularly. In step 3, the entire conchal bowl was sutured perpendicularly to the main base to create 3D projection (Figure 3). The helical rim was constructed by suturing a 1-mm-thick slice of cartilage (inferior portion of rim) to the EMR-reshaped, 2-mm-thick slice of cartilage (superior portion of rim). In step 4, the entire helix was sutured perpendicularly to the main base, and the superiormost region was sutured to the cartilage foundation to create the cymba concha. The antihelix, including the antihelical crura,
A-C, Three 1-mm-thick slices of cartilage were cut into shape with the templates to create the main base. D and E, Next, the conchal bowl was created using two 1-mm-thick slices of cartilage that were sutured together perpendicularly and then sutured to the main base to create the 3D projection of the conchal bowl. F and G, The helical rim was assembled using one 2-mm-thick slice (F) and one 1-mm-thick slice (G) of cartilage and was sutured perpendicularly to the foundation cartilage. H and I, The helix, including the helical crus, was created using 2 pieces of cartilage overlaid on top of the foundation cartilage and secured with sutures. J, A thick residual segment of cartilage was secured to the inferiormost portion of the scaffold to form the antitragus. K, A 3D printed scaffold was created to aid in reproducibility and better understanding of the assembly process.

was created in step 5 using two 1-mm-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. In step 6, a thick residual segment of cartilage intended for the antitragus was secured to the inferiormost portion of the scaffold using either Derma Bond (Ethicon US, LLC) or suture. Finally, a scalpel was used to smooth any sharp edges and make any subtle final adjustments.

An iterative approach was applied to create 10 auricular cartilage frameworks and resulted in the final assembly process described above. The process lasted, on average, 1 to 2 hours to complete each ear.

Assessment of Scaffold Morphology
Six board-certified facial plastic surgeons, 3 pediatric otolaryngologists, and 1 plastic surgeon were surveyed (eTable in the Supplement) to evaluate the aesthetics, mechanical stability, and clinical feasibility of the final scaffold assembly. Each surgeon was asked to inspect 3 different frameworks (ear A, B, and C) (Figure 4). 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 2 mm thick) of modeling clay (Polyform Products Co) to simulate a soft-tissue layer (eg, temporoparietal fascia) (Figure 4C).35 Ear C (Figure 4C) was a porous polyethylene implant (MedPor implant; Stryker) also covered with a 2-mm-thick clay layer. In addition to the process used with ear A, the surgeons were blinded with respect to which clay-covered ear contained either the autologous cartilage or porous polyethylene implant. For each ear, surgeons subjectively rated the aesthetic acceptability of specific outer auricular structures as classified by Tolleth.36 For ear A, mechanical stability was also surveyed. Furthermore, the surgeons were asked general questions regarding the MCA method to assess clinical adoption feasibility and to compare it with conventional methods (ie, Tanzer2 and Brent3 methods). Responses were graded using a 5-point Likert scale, with responses ranging from 1 (disagree with the statement) to 5 (agree with the statement). Thus, a higher score represents that the surgeon agrees that the scaffold is structurally and aesthetically acceptable and feasible. Surgeons were also asked to numerically rank the aesthetic importance of each outer auricular structure with regard to which structures contribute the most to auricular aesthetics (eTable in the Supplement).

Results

Cartilage Scaffold
A projected, anatomically correct, sturdy cartilaginous scaffold was created using only cartilage obtained from the fifth porcine rib (ranging from 8 to 12 cm long by 1 to 2 cm wide). The scaffold constructed was 6.8 cm long, 3.0 cm wide, and 10 mg in weight, which is consistent with average pinna sizes (Figure 5).37

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 size is consistent with those reported in previous studies.22

Assessment of Aesthetic Acceptability, Sturdiness, and Feasibility for Clinical Use
Most of the 10 surgeons (6 [60%]) agreed that the most important aesthetic features of an ear were the contours of the auricle, followed by the lateral projection from the head and size. The relative aesthetic importance of specific auricular structures was ranked as follows: helix and antihelix (most important), concha, lobule, tragus, antitragus, and fossa triangularis (least important).

Ear A (cartilage framework without clay cover) met minimum acceptability requirements, and all substructure rat-
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ings ranged from 3.3 to 4.8. (Score range is 1 to 5 on a Likert scale; a higher score indicates that the surgeon agrees that the scaffold is structurally and aesthetically feasible.) The stability and sturdiness of the auricular framework was deemed sufficiently stable for potential clinical use, with mean (SD) ratings of 4.6 (0.70) and 4.2 (0.92), respectively. Ear B (cartilage scaffold embedded under a clay cover) met minimum morphologic acceptability requirements, with ratings of 3.5 (1.27) and higher. In addition, ear B was rated better than or equal to ear C (alloplast implant embedded under clay mold) regarding its morphologic acceptability (4.42 [0.48] vs 3.87 [0.41]; \( P = .13 \)). The only auricular structure on ear B that was scored significantly higher than ear C was the helix/antihelix (ear B helix/antihelix, 4.6 [0.97] vs ear C helix/anti-helix 3.5 [1.27]; \( P = .007 \)). There was no statistically significant difference found between ears B and C for other surface features (\( P > .05 \)).

Collectively, the entire MCA process (1) compared favorably with conventional methods (3.9 of 5), (2) created a scaffold resembling a human ear (4.3 of 5), and (3) was found to be suitable for both pediatric microtia repair and adult auricular reconstruction (4.3 and 4.2 of 5, respectively) (eFigure in the Supplement).

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.38 We believe that the MCA approach could address the shortcomings of carving-based approaches and is a potential paradigm shift in microtia repair. 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- to 2-mm-thick rib slices, are carefully designed such that construction of an auricular scaffold follows a systematic, easy-to-follow, standardized approach.39,40 Our findings suggest that this approach produces an acceptable framework although refinement of the specific factors will be needed.

Crafting the modular components for framework assembly was achieved through the precise sectioning of costal cartilage and reshaping the helical component. The cutting device used herein sections a single rib into uniform slices that are 1 to 2 mm thick. This device has been used in rhinoplasty surgery and is sold commercially.18,19 It requires some practice, typically using porcine rib, to achieve a level of comfort and familiarity. In contrast to the cartilage cutter, EMR is an experimental technology in which electrodes connected to a
simple direct-current power supply are inserted into tissue to create in situ redox reactions that lead to accelerated stress relaxation and shape change.\textsuperscript{20-29} The technique is straightforward, time efficient, and easy to sterilize. The device is cost-effective, since it requires just AA batteries and low-cost electrodes. In addition, tissue injury is highly localized and comparable to gentle morselization.\textsuperscript{20-29}

The MCA approach demonstrated here represents a starting point. Future iterations will amount to different tessellation patterns and better framework designs. In addition, a substantial amount of suturing is required for the MCA approach compared with conventional methods, and it is estimated that the entire protocol would take approximately 1 hour 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 compared with grafts made via traditional carving methods. However, the use of a temporoparietal fascial flap may eliminate this possible complication. Temporoparietal fascial flaps with full-thickness skin grafts are now more widely used owing to the introduction of porous polyethylene implants. Current literature\textsuperscript{41-46} supports the use of tempo-

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**Figure 4. Specimens Evaluated by Surgeons to Determine Scaffold and MCA Approach Feasibility and Acceptability**

A. Autologous auricular scaffold made from the MCA 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). The ruler is in inches (to convert to centimeters, multiply by 2.54).

**Figure 5. Scaffold Projection**

A. Straight-on view B. Lateral view

Lateral and straight-on views of the scaffold demonstrating adequate lateral projection. A. Straight-on view of the scaffold. B. Lateral view of the scaffold. The ruler is in inches (to convert to centimeters, multiply by 2.54).
roparietal fascial flaps covered by full-thickness skin grafts in both alloplast and autogenous microtia repair.

The focus group evaluation used in this study determined that, at this time, the MCA scaffold achieves aesthetic acceptability, attains appropriate size feasibility for clinical use, and compares favorably to widely used alloplast implants. The survey outcomes also demonstrated that MCA is potentially equal to conventional methods. One factor to consider is that the tragus was not present in either model; 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 the soft-tissue skin layer merits discussion. The thickness of this layer over either the cartilage scaffold or the porous polyethylene implant scaffold is biased and limited by the surgeon's skill and subjectivity (in this case, J.R.G.), especially in the lobule, which was created de novo for each ear. Although the surgeon attempted to maintain a uniform 2-mm-thick layer, it was difficult to control the thickness over the entire surface. Regardless, 2 mm is a practical thickness to work with when using clay and compares favorably with the measurements of skin thickness over the human ear. Alternative approaches to simulate the skin soft-tissue layer are limited. A silicone scaffold covering was considered. However, immersing the scaffold in the polymer did not allow for control over auricular definition, lobule creation, or thickness of the covering. Small animal models also fail to adequately represent soft-tissue coverings owing 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 the skin and soft-tissue layer.

The survey required in-person meetings with one investigator (J.R.G.), which may have led to score inflation. This approach, however, was deemed integral to adequately define the project's objectives and details of the protocol, which could not be accomplished otherwise. The focus group population was small (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. 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 and Boahene that use skin punch biopsy instruments to sculpt cartilage for microtia repair. However, the first steps are presented herein. Our laboratory is 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 seventh rib provides the most amount of costal cartilage and would be sufficient to construct an MCA auricular scaffold.

Overall, 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.

Conclusions
This study establishes a modular component assembly approach for the construction of an auricular scaffold for microtia reconstruction that reduces cartilage and minimizes procedural difficulty. Modular component assembly 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 that the MCA approach is a starting point for a new cartilage-conserving and standardized microtia reconstruction method.


