Pursuing Mirror Image Reconstruction in Unilateral Microtia: Customizing Auricular Framework by Application of Three-Dimensional Imaging and Three-Dimensional Printing

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Background: Advances in three-dimensional imaging and three-dimensional printing technology have expanded the frontier of presurgical design for microtia reconstruction from two-dimensional curved lines to three-dimensional perspectives. This study presents an algorithm for combining three-dimensional surface imaging, computer-assisted design, and three-dimensional printing to create patient-specific auricular frameworks in unilateral microtia reconstruction.
Methods: Between January of 2015 and January of 2016, six patients with unilateral microtia were enrolled. The average age of the patients was 7.6 years. A three-dimensional image of the patient's head was captured by 3dMDcranial, and virtual sculpture carried out using Geomagic Freeform software and a Touch X Haptic device for fabrication of the auricular template. Each template was tailored according to the patient's unique auricular morphology. The final construct was mirrored onto the defective side and printed out with biocompatible acrylic material.
Results: During the surgery, the prefabricated customized template served as a three-dimensional guide for surgical simulation and sculpture of the MEDPOR framework. Average follow-up was 10.3 months. Symmetric and good aesthetic results with regard to auricular shape, projection, and orientation were obtained. One case with severe implant exposure was salvaged with free temporoparietal fascia transfer and skin grafting.
Conclusions: The combination of three-dimensional imaging and manufacturing technology with the malleability of MEDPOR has surpassed existing limitations resulting from the use of autologous materials and the ambiguity of two-dimensional planning. This approach allows surgeons to customize the auricular framework in a highly precise and sophisticated manner, taking a big step closer to the goal of mirror-image reconstruction for unilateral microtia patients. (*Plast. Reconstr. Surg.* 139: 1433, 2017.)
CLINCIAL QUESTION/LEVEL OF EVIDENCE: Therapeutic, IV.

The advent of three-dimensional imaging and printing technology has revolutionized the ability to provide personalized health care. Combining computer-assisted design and computer-assisted manufacturing, we can customize medical devices with higher accuracy for improved effectiveness. With regard to microtia reconstruction, the ultimate goal is to produce symmetric

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ears in terms of size, position, projection, and three-dimensional geometry. Currently, there are still obstacles to creating "identical ears" bilaterally.

The success of auricular reconstruction depends on two elements, the framework for shape and structural support and the soft tissue for coverage. In 1959, Tanzer was the first to describe the principles of multistage surgery for total auricular reconstruction using carved costal cartilage as the framework.[1] Multiple modifications have been made to improve aesthetic results and decrease complication rates.[2] Nagata reduced the number of stages of surgery and further elucidated the intricate convolution of the ear by creating a four-level three-dimensional cartilaginous framework to mimic the normal ear contour.[3] Autologous microtia reconstruction with costal cartilage remains the mainstream treatment. However, inevitable variables in the sculpturing process could compromise the symmetry and actual presentation of the auricular framework. These variables include the shape and quality of costal cartilage, the shape of the normal ear, and surgical execution. Although the use of costal cartilage provides the benefits of good tissue matching and stable coverage of the framework, the presence of existing variables makes it impossible to achieve mirror-image reconstruction for our patients.

In the pursuit of early surgery and the absence of donor-site morbidity, Reinisch and Lewin have pioneered alloplastic auricular reconstruction with high-density porous polyethylene as a reasonable and appealing alternative. By the incorporation of temporoparietal fascia coverage and full-thickness skin graft, consistent and favorable results could be achieved in a single-stage operation.[4] One invaluable advantage is that the sky is the limit in terms of shaping high-density porous polyethylene for microtia reconstruction. It is easy to cut or trim with surgical instruments, and its thermoplastic property allows bending by placing the material in hot water (>82°C). In this way, the auricular framework can be delicately fabricated to the desired shape and size.

In practice, most surgeons use the high-density porous polyethylene auricular implant already present on the market currently, which consists of a preformed helical rim and a base block. However, few alterations can be made to simulate the various characteristics of each individual's ear. The conchal depth, lobule curvature, and wavy contour of the helix from the lateral view are not easily addressed, and the tragus is often insufficient to create the illusions of an ear canal. Although it is convenient, the preexisting high-density porous polyethylene auricle is unlikely to create a mirror image of the normal ear. In contrast, customizing the high-density porous polyethylene framework by manual sculpturing provides the benefit of being able to reproduce the configuration of the patient's normal ear with unsurpassed finesse and accuracy. However, the complexity of the ear's convolutions can sometimes discourage budding surgeons.[5]

Three-dimensional surface imaging is a powerful adjunct in the field of craniofacial surgery in terms of preoperative planning, outcome simulation, and treatment evaluation.[6,7] For microtia reconstruction, the use of 3dMDcranial (3dMD, Atlanta, Ga.) in the measurement of ear anthropometry has been proven to be accurate and reproducible.[8] Although the quest for a "three-dimensional printed ear" is ubiquitous, few studies have adopted the technology in fabrication of the auricular framework for microtia surgery. Since September of 2012, we have routinely used life-size auricular models derived from the surface images of the patient's normal ear taken by 3dMDcranial as a surgical guide for microtia reconstruction. When used in conjunction with computer-assisted design, we can further refine the three-dimensional model into a ready-to-use implantable framework of the ear, which can be manufactured directly with the appropriate biocompatible material.

PATIENTS AND METHODS

Three-Dimensional Image Acquisition and Digitalization

This study was approved by the Chang Gung Medical Foundation Institutional Review Board. Between January of 2015 and January of 2016, six patients with unilateral microtia who underwent ear reconstruction using high-density porous polyethylene (MEDPOR; Stryker, Kalamazoo, Mich.) implants were enrolled. The average age of the patients was 7.6 years (range, 5 to 11 years). Three patients had a variable degree of hemifacial microsomia (Table 1). Before surgery, standard two-dimensional photographs of the patient's head were obtained. Digital three-dimensional images of the patient's head were captured using the 3dMDcranial system. To attain maximal quality and ensure optimal capture of the contours of the auricular surface during imaging of the external ears, the patient was rotated 360 degrees, with the three-dimensional images taken at 45-degree intervals. Three-dimensional images for each patient were reviewed using the 3dMDvultus Software (3dMD), and the set with the most detailed anatomical information of the normal ear was exported in a stereolithography (*.STL) file format (Fig. 1).

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Table 1. Patient Information

Patient	Sex	Age (yr)	Microtia Side	Microtia Type	Associated Craniofacial Deformities	Follow-Up (mo)	Complications	Additional Procedures
1	M	6	R	Small concha	—	06	—	—
2	F	11	R	Small concha	—	19	—	—
3	M	11	R	Small concha	—	07	Transitory alopecia	—
4	M	7	R	Lobule	Right hemifacial microsomia, right macrostomia	18	—	—
5	M	6	R	Lobule	Right hemifacial microsomia	06	Transitory alopecia	—
6	F	5	L	Lobule	Left hemifacial microsomia, left incomplete facial palsy	06	Early implant exposure because of TPFF loss	Free TPFF transfer, STSG

M, male; F, female; R, right; L, left; TPFF, temporoparietal fascia flap; STSG, split-thickness skin graft.

Data Processing and Template Fabrication

The STL file of the head was imported into Geomagic Freeform Software (3D Systems, Rock Hill, S.C.), where it became "digital clay." The Geomagic Touch haptic device (3D Systems) was used to modify the extraneous artifacts and subtract the skin thickness. Crucial anatomical features of the normal ear and their spatial relationship were carefully delineated and restored on an individual basis (Fig. 2). The constructed model was mirrored to the affected side relative to the facial midline and the microtic ear was removed. The optimal orientation of the reconstructed ear was determined based on the frontal view (Fig. 3). Then, a base block was added behind the template framework for projection, accommodating the contours of the posterior surface of the framework and that of the underlying mastoid region. The final framework and base block template was manufactured with biocompatible PolyJet photopolymer (MED 610) on the Object30 Prime 3D printer (Stratasys, Rehovot, Israel).

RESULTS

Prefabricated Customized Auricular Template for Surgical Guidance

Single-stage auricular reconstruction with MEDPOR implants was performed. The prefabricated framework template was used to simulate the facial appearance after ear reconstruction and to confirm ear location. The two-dimensional outline of the normal ear contour was projected on the planned implant site. The course of the superficial temporal artery was traced using the hand-held Doppler device. The incision was designed using the Nagata method, and a crescent-shaped, ultradelicate, split-thickness skin graft was elevated in continuity with the skin flap. The lobule flap was created. The vestigial cartilage and remnant soft tissue above the fascia within the area of planned reconstruction were removed. The prefabricated auricular template was inserted to simulate the draping of skin flap and lobule flap and estimate the area requiring fascia flap coverage (Fig. 4). The temporoparietal fascia flap was elevated from the auricular incision. A large flap, at least 10 cm in width and 12 cm in length measured from the upper border of the planned helix location, was elevated to ensure adequate coverage of the implant.

The implantable auricular framework and the projection block were carved from a MEDPOR block (38 × 63 × 9.5 mm) with blades, gouges, and burrs. The prefabricated template served as an important reference for the intricate convolution of the normal ear, facilitating the sculpting process without turning the patient's head back and forth. We were able to obtain close resemblance of the auricular framework with the normal ear (Fig. 5). The curvature of the auricle can be molded by submerging MEDPOR into a hot saline bath and bending it to the desired shape. The base block template provided an idea of the support required for stable symmetric projection, thereby aiding in the fabrication of the implantable projection block. The final implantable framework and projection block were combined with double-armed stainless steel wires.

The completed MEDPOR implant was placed on the predetermined position and fixed with 4-0 polydioxanone (Ethicon, Inc., Somerville, N.J.) sutures. The temporoparietal fascia flap was turned down to envelop the implant. The lobule flap was transposed to the lobule portion of the framework. A suction drain was inserted between the fascia flap and the framework. The anteriorly based skin

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Fig. 1. Three-dimensional images of the patient's head are captured by means of the 3dMDcranial system.

flap in continuity with a split-thickness skin graft was redraped over the fascia-enveloped MEDPOR implant. The residual raw surface was grafted with split-thickness skin graft harvested from the scalp. After all wounds were closed, a light compressive dressing was placed over the reconstructed ear.

CASE REPORTS

All patients underwent single-stage auricular reconstruction with customized MEDPOR implants. Average follow-up was 10.3 months (range, 6 to 19 months). Transitory alopecia in ipsilateral scalp was observed in two patients, and the hair grew up 3 to 4 months after the operation. One patient with severe ipsilateral hemifacial microsomia had early implant exposure caused by inadequate circulation of the hypoplastic fascia flap and underwent a salvage procedure with free temporoparietal fascia flap transfer from the contralateral side, using facial vessels as recipients. Symmetric aesthetic results with regard to auricular shape, projection, and orientation were obtained in five patients who had uneventful healing (Table 1).

Fig. 2. The extraneous artifacts are removed from the surface model. After virtual sculpture, we can obtain the auricular framework (*solid part*) beneath the skin envelope (*transparent part*), resembling the convolutions of a normal ear.

Case 1

A 7-year-old boy presented with right small concha-type microtia (Fig. 6). The three-dimensional image of the patient's head was acquired using the 3dMDcranial system and imported into Geomagic Freeform Software. The framework template was fabricated virtually, replicating the characteristic features of his normal ear. We used the template to determine the position of the reconstructed ear and design the incision. After elevation of the skin flap, insertion of the template simulated the appearance after skin flap draping and helped to estimate the size of the soft tissue needed for coverage. The implantable framework and projection block were carved from a single piece of MEDPOR, and the prefabricated template served as a three-dimensional sculpting guide. After fixation of the MEDPOR framework, the temporoparietal fascia flap was harvested to cover the implant, followed by redraping of skin flaps and split-thickness skin grafting (Fig. 7). Six months after surgery, the projection, position, and shape of the reconstructed ear along with its curvature from the posterior view were satisfactory (Fig. 8).

Case 2

An 11-year-old girl presented with right small concha-type type microtia (Fig. 9). Single-stage reconstruction with a MEDPOR implant was performed (Fig. 10). The individualized auricular template generated from the three-dimensional images captured by 3dMD and using computer-assisted design and computer-assisted manufacturing assisted the surgeon in precise sculpturing of the custom MEDPOR framework. Eight months after surgery, the shape

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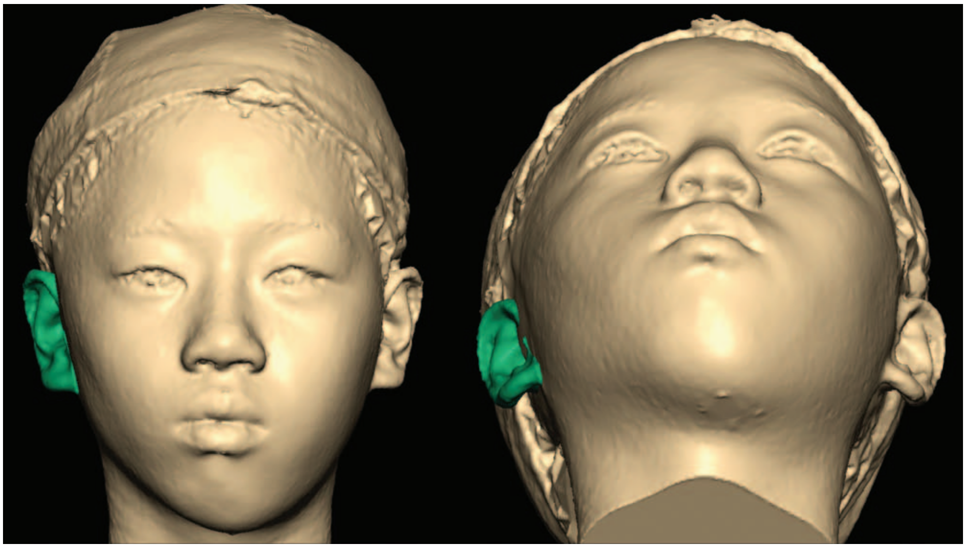

Fig. 3. The construct model is mirrored to the microtia side (*green*). The optimal position and orientation can be adjusted until symmetry is obtained.

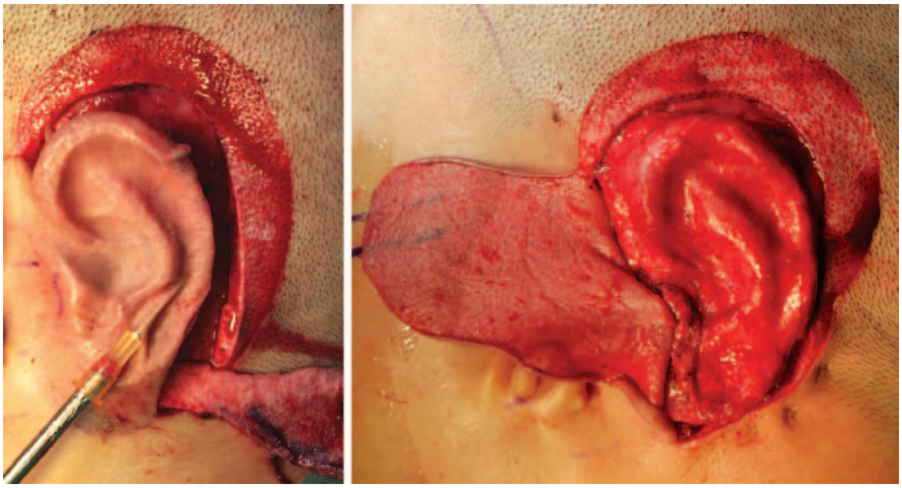

Fig. 4. The skin flap was draped over the prefabricated template. Lobule tissue was insufficient to provide distal coverage (*right*). Thus, a longer temporoparietal fascia flap was required to ensure complete wrapping of the implant (*left*).

of the reconstructed ear was similar to the normal ear in terms of fine details. Good projection and position were obtained (Fig. 11).

DISCUSSION

Achieving mirror-image reconstruction is a challenge in microtia reconstruction. Although there are anthropometric measurements of the external ear, the reference landmarks that surgeons use to reproduce a normal ear are mostly presented two-dimensionally.[9,10] Systematic errors are unavoidable when transforming a three-dimensional structure into a two-dimensional slice.[11,12] Loss of three-dimensional perception is critical in framework fabrication because the intricate convolutions of human ears are difficult to mimic. A three-dimensional imaging system provides shape-fidelity of the external ear and transforms it into manufacturing output files. In conjunction with computer-assisted design and computer-assisted manufacturing, this creates the possibility of a patient-specific auricular implant, matching the characteristic prominences and depressions of the contralateral normal ear.[13]

Acquiring Three-Dimensional Images of the Normal Ear

The crucial first step is to acquire a three-dimensional geometric model of the patient's

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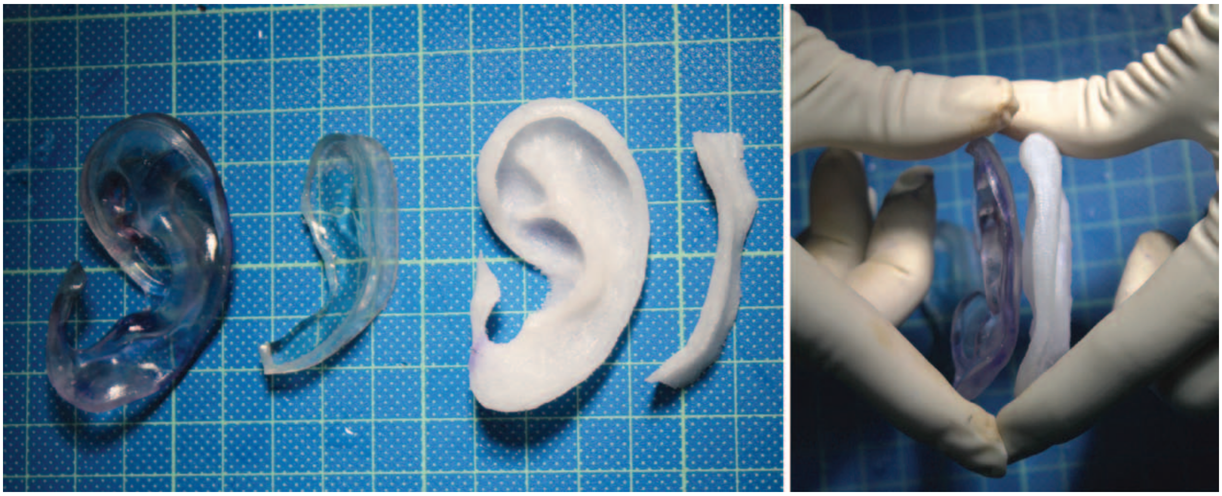

Fig. 5. The prefabricated template and base block (*transparent*) guides the carving process of the MEDPOR framework (*white*) to replicate the convolutions, eminences, and depressions of a normal ear.

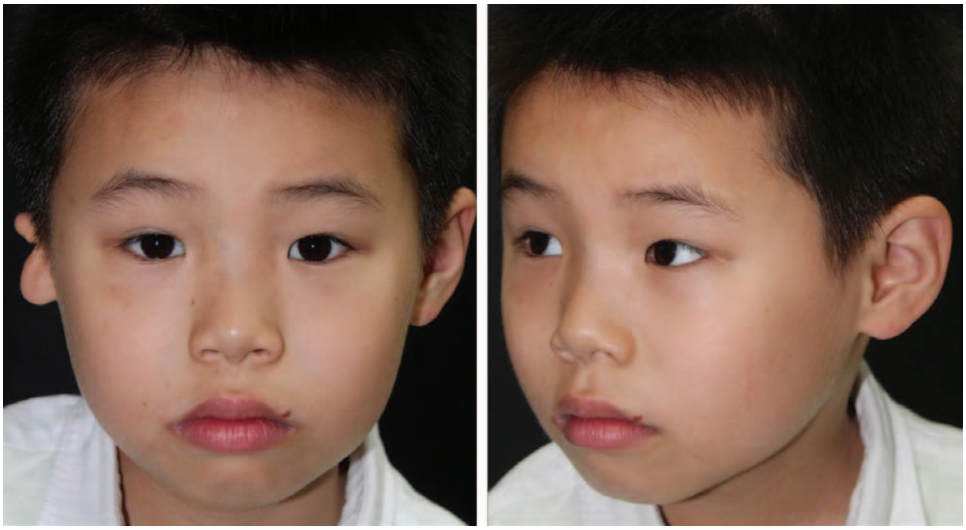

Fig. 6. A 7-year-old boy with right small concha-type microtia.

normal ear, which is fundamental for framework construction. The scanning process should be noninvasive, precise, accurate, and fast. One of the most common techniques is computed tomography, which yields the true interior structural data of the target object by acquiring its volumetric pixels in a large series of two-dimensional radiographic images, and forming the three-dimensional model by stacking the two-dimensional slices together. In contrast to computed tomography, three-dimensional surface imaging technology measures and analyzes surfaces of the target object along *x*, *y*, and *z* coordinates in three-dimensional space and generates a point cloud representing the external contour of the object for three-dimensional visualization and processing.[6,7,14] It is noninvasive and obviates the risk of radiation exposure. Among different techniques, optical-based surface imaging systems using structural light or stereophotogrammetry technology have evolved greatly over the past two decades and gained prominence in clinical and research applications.[6,7]

The 3dMD technology combines both active and passive stereophotogrammetry and the 3dMDcranial system features (1) full 360-degree surface coverage of the head in a single capture, (2) an ultrafast acquisition speed of 1.5 msec, and (3) geometric accuracy with less than 0.2 mm root mean square. Many studies have validated the 3dMD system in craniofacial

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Fig. 7. Preoperative design. The template helped to simulate the position of the reconstructed ear (*above*, *left*). The prefabricated template served as a three-dimensional sculpting guide (*below*). The MEDPOR framework was covered by a temporoparietal fascia flap and resurfaced with anteriorly based skin flaps and split-thickness skin grafts (*above*, *right*).

measurements.[15–17] Chen et al. showed that the 3dMDcranial system provided better precision and reliability in terms of obtaining anthropometry of the auricle than direct measurement.[8] The three-dimensional surface imaging modalities overcome errors from patient movements and distortions caused by direct contact. In addition, three-dimensional digital representations allow repeated evaluations and comparisons in software platforms. The speed, reliability, and safety of the 3dMD system make it an invaluable tool for quantification of craniofacial features, particularly for young children.[18]

Creation of an Individualized Auricular Implant

The convergence of three-dimensional technologies and computer-assisted design and computer-assisted manufacturing can be a game-changer in contemporary microtia reconstruction, which has the potential of providing microtic patients with a mirror image of their normal ear. However, most of its uses have been exclusively in building tissue-engineering scaffolds and design of ear prostheses rather than customizing the implantable auricular framework for microtia surgery.[19–25] Zopf et al. used computed tomographic imaging to design a

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Fig. 8. Six months after surgery, with good projection and shape of the reconstructed ear.

three-dimensional bioscaffold.[22] Besides replicating the external contour, Staudenmaier et al. and Zeng et al. delineated the cartilaginous portion of the auricle from the surrounding tissues on the computed tomographic scan by selecting the thresholds of their corresponding pixel values and converting the segmentation data into a three-dimensional representation of the auricular cartilage.[23,24] With the advantage of avoiding ionizing radiation, three-dimensional laser scanning has been used to acquire the external geometry of the auricle to design a mold for deposition of cell-containing hydrogels.[25] The results in regenerating the auricle seem promising; however, major challenges, including provision of a suitable microenvironment for tissue maturation and creation and maintenance of the auricular shape with suitable biomaterials, still hamper its clinical applications.[26]

Fig. 9. An 11-year-old girl with right small concha-type microtia.

Auricular reconstruction is an aesthetic procedure, and a personalized approach is required to achieve an optimal outcome for each patient. Differences in auricular geometry, implant properties, and surgical experience and technique, along with tissue condition at the recipient site, account for the unpredictability of outcome. It is intuitive, for both surgeons and patients, to adopt the advances in three-dimensional imaging and manufacturing technology to create individualized auricular frameworks and perform the surgery in a more controlled and efficient manner. Park et al. have used computed tomographic imaging and stereolithography, without subtracting soft-tissue thickness, to generate three-dimensional templates of the normal ear to facilitate cartilage carving.[11] Gandy et al. divided the three-dimensional template into multiple smaller components to guide the cutting of cartilage slices for assembly into a complete framework.[27] Bos et al. developed a customizable parametric model, in which the common anatomical features of the ear can be manipulated individually to match the distinctive shape of various auricular cartilage obtained from computed tomographic scans.[28] The design of auricular constructs should consider not only the shape, but also the manufacturing feasibility, implantation stability, and adaptability to limitations imposed by soft-tissue coverage and underlying support.

When using alloplastic materials for auricular reconstruction, the restored ear consists of a framework draped by a layer of soft tissue,

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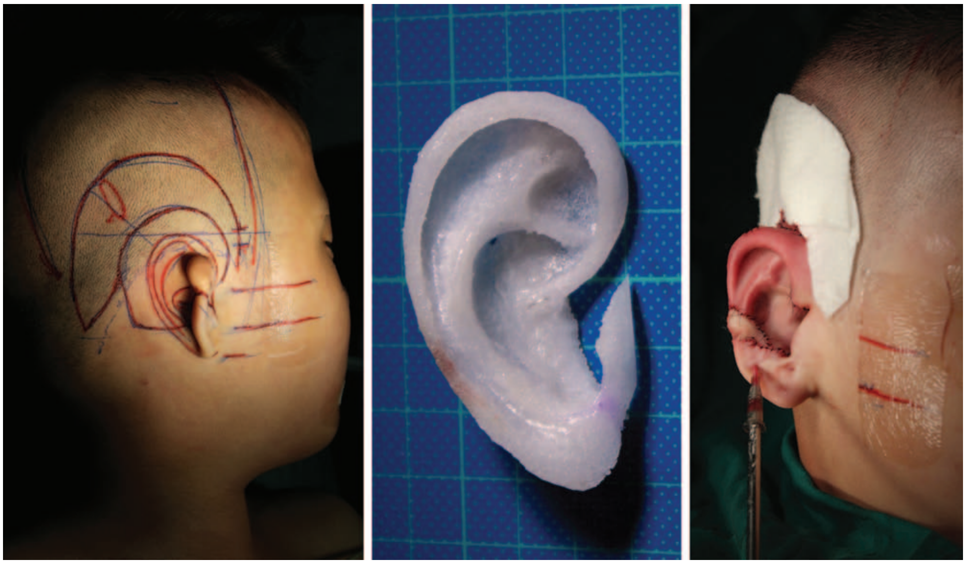

Fig. 10. Preoperative design (*left*). Customized MEDPOR implant (*center*). Postoperative photograph (*right*).

composed of fascia flaps and skin grafts. This concept helped us to retrieve the framework architecture by subtracting the soft-tissue thickness from the external contour of the normal auricle.[29,30] The model can be adjusted to accommodate the recipient site. We can alter the thickness of the lobule according to the native lobular tissue and the conchal depth depending on the adequacy of fascia coverage. Compared with the commercial MEDPOR auricular implant, the model in this study maintained the mirror image of the normal ear with greater symmetry and accuracy. Moreover, the three-dimensional database of all the normal ears could be used as a template for patients with bilateral microtia.

Limitations

This study had several limitations. Three-dimensional surface images taken by the 3dMDcranial system often had artifacts where the ambient light was obstructed during capture, such as the undersurface of the helix, conchal cavities, the retrotragal region, and the posterior surface of the auricle. Efforts to remove digital noise and recreate the actual contour might result in inaccuracy in subsequent design of the auricular construct. We are currently investigating the feasibility of using other three-dimensional scanning modalities to improve the precision of acquired data.

Although digital models of auricular frameworks can be designed precisely, there are limitations in the choice of suitable customizable alloplastic materials for the auricular framework. This is the major obstacle to producing ready-to-use patient-specific implants for microtia reconstruction. On the one hand, the customized MEDPOR implants have not yet been approved by the Taiwan Food and Drug Administration Regulations for Medical Devices, and we had to convert the electronic designs into the implantable frameworks by manual sculpting to carry out our idea. We acknowledge the time and effort required in addition to unavoidable human errors related to hand carving, but we believed it was of substantial value to address individuality in auricular reconstructions in the era of personalized medicine. On the other hand, although there are burgeoning applications in three-dimensional imaging, computer-assisted design and computer-assisted manufacturing, and three-dimensional printing technology with regard to building personalized medical devices, more progress is needed in the development of biocompatible materials for the auricular framework.

Last but not least, soft tissue plays a vital role in the final appearance of the reconstructed ears. The state of native tissue, adequacy of soft-tissue coverage, stability of grafted skin, and the healing process will determine the ultimate definition and projection of the reconstructed ear. The ongoing debate between autologous and alloplastic reconstructions is beyond the scope of this study, but it is clear that each procedure has its pros and cons. The ultimate advantage of using an alloplastic framework is to avoid donor-site complications. The high-density porous polyethylene implant can be made precisely as a mirror-image of each patient's normal ear with delicate thinness, yet can

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Fig. 11. Eight months after surgery. The reconstructed ear was symmetrical to the normal ear regarding shape, position, and projection.

maintain structural stability. There is no chance of resorption. Single-stage surgery can be performed in early childhood. However, soft-tissue conditions are more critical when using alloplastic materials compared with costal cartilage, deserving special attention so that consistent results can be achieved. The postoperative skin quality and color may be unpredictable resulting from suboptimal fascial coverage and skin grafting. Although infrequent, there are risks of implant exposure, which may necessitate additional procedures to provide vascularized soft-tissue coverage. When the fascia circulation is not robust, especially in patients with hemifacial microsomia, staged operations are required. By contrast, soft-tissue management in autologous reconstruction is more forgiving, obviating the exposure events. Because the cartilage can be placed directly under a single layer of skin pocket, the skin color and texture are noted to be superior. However, uncontrollable factors regarding the shape, quality, and quantity of costal cartilage in each patient often hamper the surgeons in producing the framework as an exact copy of the normal ear. Also, the risks of resorption may adversely affect the outcomes.

CONCLUSIONS

We have successfully incorporated three-dimensional surface imaging and three-dimensional printing technology to produce personalized three-dimensional auricular models

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before ear reconstruction at our center. This is a useful tool that allows surgeons to build a customized auricular framework in a highly precise manner, which in turn improves the aesthetics and symmetry in reconstruction. In the future, development of a three-dimensional, image-guided system, in conjunction with automated manufacturing of a patient-specific biocompatible auricular framework, can significantly improve surgical accuracy and efficiency. Possibly, this can serve as a bridge between current microtia reconstruction techniques using costal cartilage or alloplastic material and the era of tissue-engineering–based reconstruction.

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PATIENT CONSENT

Parents or guardians provided written consent for the use of patients' images.

REFERENCES

1. Tanzer RC. Total reconstruction of the external ear. *Plast Reconstr Surg Transplant Bull.* 1959;23:1–15.
2. Baluch N, Nagata S, Park C, et al. Auricular reconstruction for microtia: A review of available methods. *Plast Surg (Oakv.)* 2014;22:39–43.
3. Nagata S. A new method of total reconstruction of the auricle for microtia. *Plast Reconstr Surg.* 1993;92:187–201.
4. Reinisch JF, Lewin S. Ear reconstruction using a porous polyethylene framework and temporoparietal fascia flap. *Facial Plast Surg.* 2009;25:181–189.
5. Chen ZC, Chen PK, Hung KF, Lo LJ, Chen YR. Microtia reconstruction with adjuvant 3-dimensional template model. *Ann Plast Surg.* 2004;53:282–287.
6. Tzou CH, Frey M. Evolution of 3D surface imaging systems in facial plastic surgery. *Facial Plast Surg Clin North Am.* 2011;19:591–602, vii.
7. Chang JB, Small KH, Choi M, Karp NS. Three-dimensional surface imaging in plastic surgery: Foundation, practical applications, and beyond. *Plast Reconstr Surg.* 2015;135:1295–1304.
8. Chen ZC, Albdour MN, Lizardo JA, Chen YA, Chen PK. Precision of three-dimensional stereo-photogrammetry (3dMD) in anthropometry of the auricle and its application in microtia reconstruction. *J Plast Reconstr Aesthet Surg.* 2015;68:622–631.
9. Tanzer RC. Total reconstruction of the auricle: The evolution of a plan of treatment. *Plast Reconstr Surg.* 1971;47:523–533.
10. Brent B. Auricular repair with autogenous rib cartilage grafts: Two decades of experience with 600 cases. *Plast Reconstr Surg.* 1992;90:355–374; discussion 375.
11. Park GC, Wiseman JB, Clark WD. Correction of congenital microtia using stereolithography for surgical planning. *Plast Reconstr Surg.* 2000;105:1444–1447.
12. Kelley TF, Moulton-Barrett R, Dugan FM, Crumley RL. The use of 3-dimensional models in auricular reconstruction. *Arch Otolaryngol Head Neck Surg.* 1998;124:335–338.
13. Gerstle TL, Ibrahim AM, Kim PS, Lee BT, Lin SJ. A plastic surgery application in evolution: Three-dimensional printing. *Plast Reconstr Surg.* 2014;133:446–451.
14. Markiewicz MR, Bell RB. The use of 3D imaging tools in facial plastic surgery. *Facial Plast Surg Clin North Am.* 2011;19:655–682, ix.
15. Heike CL, Cunningham ML, Hing AV, Stuhaug E, Starr JR. Picture perfect? Reliability of craniofacial anthropometry using three-dimensional digital stereophotogrammetry. *Plast Reconstr Surg.* 2009;124:1261–1272.
16. Lübbers HT, Medinger L, Kruse A, Grätz KW, Matthews F. Precision and accuracy of the 3dMD photogrammetric system in craniomaxillofacial application. *J Craniofac Surg.* 2010;21:763–767.
17. Wong JY, Oh AK, Ohta E, et al. Validity and reliability of craniofacial anthropometric measurement of 3D digital photogrammetric images. *Cleft Palate Craniofac J.* 2008;45:232–239.
18. Heike CL, Upson K, Stuhaug E, Weinberg SM. 3D digital stereophotogrammetry: A practical guide to facial image acquisition. *Head Face Med.* 2010;6:18.
19. Subburaj K, Nair C, Rajesh S, Meshram SM, Ravi B. Rapid development of auricular prosthesis using CAD and rapid prototyping technologies. *Int J Oral Maxillofac Surg.* 2007;36:938–943.
20. Liacouras P, Garnes J, Roman N, Petrich A, Grant GT. Designing and manufacturing an auricular prosthesis using computed tomography, 3-dimensional photographic imaging, and additive manufacturing: A clinical report. *J Prosthet Dent.* 2011;105:78–82.
21. Ciocca L, Scotti R. CAD-CAM generated ear cast by means of a laser scanner and rapid prototyping machine. *J Prosthet Dent.* 2004;92:591–595.
22. Zopf DA, Mitsak AG, Flanagan CL, Wheeler M, Green GE, Hollister SJ. Computer aided-designed, 3-dimensionally printed porous tissue bioscaffolds for craniofacial soft tissue reconstruction. *Otolaryngol Head Neck Surg.* 2015;152:57–62.
23. Staudenmaier R, Hoang NT, Mandlik V, et al. Customized tissue engineering for ear reconstruction. *Adv Otorhinolaryngol.* 2010;68:120–131.
24. Zeng W, Lin F, Shi T, et al. Fused deposition modelling of an auricle framework for microtia reconstruction based on CT images. *Rapid Prototyp J.* 2008;14:280–284.
25. Reiffel AJ, Kafka C, Hernandez KA, et al. High-fidelity tissue engineering of patient-specific auricles for reconstruction of pediatric microtia and other auricular deformities. *PLoS One* 2013;8:e56506.
26. Otto IA, Melchels FP, Zhao X, et al. Auricular reconstruction using biofabrication-based tissue engineering strategies. *Biofabrication* 2015;7:032001.
27. Gandy JR, Lemieux B, Foulad A, Wong BJ. Modular component assembly approach to microtia reconstruction. *JAMA Facial Plast Surg.* 2016;18:120–127.
28. Bos EJ, Scholten T, Song Y, et al. Developing a parametric ear model for auricular reconstruction: A new step towards patient-specific implants. *J Craniomaxillofac Surg.* 2015;43:390–395.
29. Nagata S. Modification of the stages in total reconstruction of the auricle: Part III. Grafting the three-dimensional costal cartilage framework for small concha-type microtia. *Plast Reconstr Surg.* 1994;93:243–253; discussion 267.
30. Danter J, Siegert R, Weerda H. Ultrasound measurement of skin and cartilage thickness in healthy and reconstructed ears with a 20-MHz ultrasound device (in German). *Laryngorhinootologie* 1996;75:91–94.

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