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Developing a parametric ear model for auricular reconstruction: A new step towards patient-specific implants

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ABSTRACT

Introduction: Ear reconstruction is a tedious and demanding surgical procedure and the implant framework used is essential for the esthetic result. The outcome of a reconstructed ear, however, is not necessarily limited to the implant shape but rather to the available options of transplantable tissue for coverage. Apart from the visual aesthetics, ear reconstruction subsequently also requires implant dimensions to be adapted to the surgical possibilities. In this article, we have brought different disciplines together to develop a customizable ear model for 3D printing of ear implants.
Material and methods: Computed tomography (CT) scans were made of 4 human cadaver ears before and after soft tissue dissection using a Discovery 750 High Definition Freedom Edition scanner (GE, Milwaukee, WI, USA) and subsequently converted into an STL data set using Mimics Software (Materialise, Leuven, Belgium). These scans were then used to develop a fully adjustable parametric model based on the essential ear anatomy using Rhinoceros and Grasshopper software.
Results: To determine the quality of the developed models, directed Hausdorff distance (DHD) was applied as the basis for measuring the similarity between the parametric model and the ear cartilage scanning data. Two methods were used. The mean directed Haussdorff distance (MDHD) was calculated based on the distribution of point sets showing an average similarity of 0.8 mm (±0.05 mm). The mean similarity coefficient (SC) of the model and scan surfaces was 94% with a 2-mm threshold.
Conclusion: This study shows that a parametric standard model could be used as a feasible method to generate custom implants based on existing ear images.

1. Introduction

Cartilage plays a key role in form and function of the nose and ears. The protruded shape of nasal and auricular cartilage and the relatively thin covering tissue make them particularly vulnerable for trauma. In addition, oncologic resection of large tumors in the maxillofacial area can result in partial or complete loss of the auricle. After the acute phase, reconstruction of facial cartilage proves to be a demanding and time-consuming process, depending on the extent of damage. Current clinical ear cartilage reconstruction consists basically of 2 options; carved rib cartilage as a substitute, and biocompatible artificial implants. Harvesting autologous rib cartilage to manufacture an ear frame was first described in 1969 by Tanzer and was further perfected by A.O. Brent and Nagata (Nagata, 1993). It has since evolved as the method of choice in many reconstructions (Park et al., 1999). Synthetic implants have quite extensively been used in microtia and trauma ear reconstruction (Reinisch and Lewin, 2009; Braun et al., 2010), but only a few reports exist specifically in burned ear reconstruction (Wellisz, 1993; Driscoll and Lee, 2010). Both techniques have different advantages and disadvantages. They have 1 thing in common, however: The implant, be it costal cartilage or plastic, has to be manually cut and

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trimmed by the surgeon to achieve the desired ear shape. With rapidly evolving 3-dimensional (3D) printing and imaging techniques, it is not surprising that several researchers have developed copies of ears for reconstruction purposes (Naumann et al., 2003; Reiffel et al., 2013; Bomhard et al., 2013). However, the shape of a reconstructed ear is dependent not only on the implant but also on the available options of transplantable tissue for coverage. Brent, in 1 of his papers, pointed out that the cartilage framework needs to be adapted to these limitations: "Although one would think it must be carved to exactly mimic an auricular cartilage, instead one must take note of and make allowances for limitations imposed by abnormal skin coverage" (Brent, 1992).

This is especially the case in patients with large areas of damaged or ablated facial tissue, limited graft options, and extensive scar formation (Bhandari, 1998). The elastic skin of a juvenile microtia patient may need a less projected and more delicate implant than a reconstruction with a free radial forearm flap in an adult burn victim (Akin, 2001).

As such, the surgeon will want to be able to adapt an implant to meet these challenges. Berghaus et al. (2010), for example, concludes that Medpor, a synthetic implant of standardized shape available in several sizes, provides better definition and projection than costal rib constructs in microtia patients. However, satisfactory results using rib cartilage for reconstruction have also extensively been reported (Brent, 1994), and this is still a common treatment mode in many hospitals.

A third alternative is the use of an osseointegrated prosthesis. This is generally a last resort and reserved for patients with unfavorable reconstructive options due to extensive damage, craniofacial anomalies, or a personal preference for minimal invasive treatment (Thorne et al., 2001). The osseointegrated prothesis consists of brackets attached to the cranium and a detachable plastic ear model (Santos dos et al., 2010). Disadvantages include risk of bracket infection and wear of the prosthesis. Also, necessary shape adjustments of the prosthesis to maintain bi-auricular similarity requires replacement every few years, making ear prostheses a costly option on the long term.

We can conclude that auricular reconstruction requires not only different approaches but also adjustable implant or prosthesis dimensions. In this study, we have brought several disciplines together to develop a parametric, fully adjustable ear model applicable for 3D printing of customized ears.

2. Materials and methods

2.1. CT scans of ears

Computed tomography (CT) scans were made of 4 dissected human cadaver ears (from deceased Dutch patients) using a Discovery 750 High Definition Freedom Edition scanner (GE, Milwaukee, WI, USA). According to a routine research protocol set by the institutional medical ethics committee, the cadaver ears were provided by the Department of Anatomy of the Utrecht Medical Centre without disclosure of the medical history of the patient.

The acquired CT data sets were then subsequently converted into Stereolithography Interface Format (STL) files using Mimics Software (Materialise, Leuven, Belgium). The images were smoothed slightly before the actual segmentation (decimation factor 0.50, smoothing iterations 20). No post-segmentation smoothing or filtration was applied to the models.

2.2. Parametric model development

The human ear consists of a number of anatomical features that are similar for all individuals. However differences in factors such as angle, thickness, and protrusion make each ear unique. Based on these standard features, an ear parametric model was developed with fully adjustable anatomical structures (Fig. 1). Rhinoceros modeling software was primarily used to create a basic ear implant model (McNeel North America, Seattle, WA, USA). In order to make the acquired static model parametrically adjustable, a plug-in software Grasshopper (www.grasshopper3d.com) was used, thereby enabling manual alterations to the model dimension values in Rhinoceros. Number sliders in the Grasshopper software offered the possibility of manipulating multiple points in space of an interpolated curve to create the basic shape of the ear. To give the model its body, perpendicular planes were placed along the multiple curves, and on those planes different shapes were drawn depending on the desired specifications. For example, on the planes in the helical rim area, a half moon shape was drawn, the superior crura was shaped by an oval, and the tragus had a blob-like form. The shapes on every plane were then connected to each other to form a solid model with fluent transitions.

This basic ear model was superimposed on an STL file converted from an ear cartilage CT scan to create a matching implant. The parametric ear model was superimposed on the acquired STL-file converted ear CT image in Rhinoceros and adjusted with the Grasshopper number sliders to fit the original ear based on operator preferences (Figs. 2 and 3).

2.3. Similarity measurements

To evaluate the performance of the parametric model, first we matched it to the STL file converted from the 4 corresponding CT ear scans. The matching process was conducted semi-automatically in several iterations. The model was then registered to the scanning data automatically using Geomagic software (www.geomagic.com). The outcomes of the final registrations can be found in Fig. 4. In the figure, gray and blue shapes present the fitted parametric models and the STL files of 4 CT scans, respectively.

One of the most important factors in the evaluation of effectiveness of the proposed parametric model is the similarity between each fitted model and the corresponding STL file of the CT scans. Numerous similarity measurement methods have been defined in the literature (Veltkamp, 2001; Fotina et al., 2012). In our project, directed Hausdorff distance (DHD) was applied as the basis for measuring similarity. By converting the fitted parametric model and the corresponding STL file to high-density point sets, the fitted parametric model can be represented as $P_M = \{P_i^M \in M \mid i = 1, m\}$ and the corresponding STL file is depicted as $P_E = \{P_i^E \in E \mid i = 1, n\}$

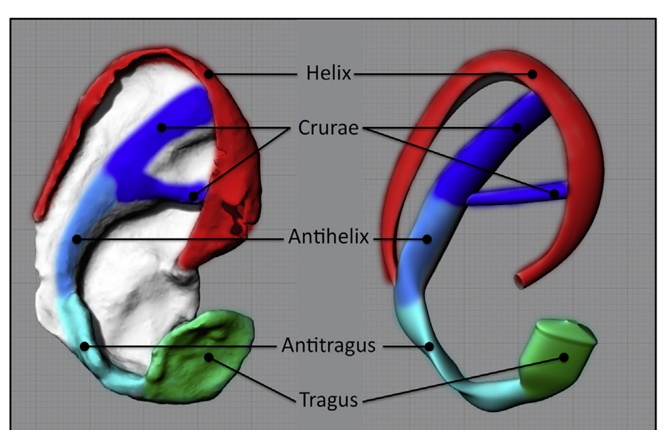

Fig. 1. Key features of standard ear anatomy compared with parametric model.