Design and Analysis of Flexible Composite Scaffolds for Engineered Ear

Thomas M. Cervantes[1], Erik K. Bassett[1], Alan Tseng[1], Anya Kimura[1], Nicholas Roscioli[3], Rajiv Gupta[2], Mark A. Randolph[4,5], Joseph P. Vacanti[1,5], Irina Pomerantseva[1,5], Cathryn A. Sundback[1,5]
Departments of [1]Surgery and [2]Radiology, Massachusetts General Hospital, Boston, MA, [3]Kensey Nash Corporation, Exton, PA, [4]Plastic Surgery Research Labs, Massachusetts General Hospital, Boston, MA, [5]Harvard Medical School, Boston, MA

Statement of Purpose: Since the 1990s, a tissue engineered ear was proposed as an option for patients with congenital and acquired ear defects. Clinical reconstruction strategies utilize costal cartilage or rigid polymer implants to recreate the complex geometry of the outer ear. However, among other disadvantages, neither approach is capable of matching the unique bending properties of native auricular cartilage (Bichara DA. Tissue Eng. Part B Rev. 2012;18:51-61). The tissue engineering methodology has the potential to address this challenge. We proposed to recreate the shape and flexibility of the native ear through use of a composite scaffold, comprised of a wire framework embedded within a porous collagen matrix (Zhou L. Tissue Eng. Part A. 2011;17:1573-81). In a proof-of-concept small animal study, we demonstrated that the framework provided enough stiffness to maintain ear geometry during neocartilage formation, without impeding the flexibility of the overall structure. The composite scaffold supported neocartilage formation, while maintaining the size and shape of the ear. Building on these results, the design and fabrication process for the composite scaffold were further developed to produce a full-sized ear scaffold and with improved geometry and mechanical properties. Imaging analysis was performed to understand the behavior of the scaffold during implantation and identify opportunities for deterministic improvements.

Methods: A 3D digital model of an adult human ear was created in CAD software in conjunction with a facial reconstructive surgeon to ensure that key features were incorporated (Fig. 1A). The ear model was used to create a negative geometry mold. The framework was fabricated by hand from titanium wire, consisting of a continuous central core surrounded by a coil sheath (Fig. 1B). Composite ear scaffolds were fabricated by Kensey Nash Corporation (Exton, PA) by casting fibrous collagen with the titanium framework in the ear-shaped mold (Fig. 1C). The scaffolds were seeded with sheep auricular chondrocytes and implanted subcutaneously in nude rats for 12 weeks. 3D surface images of the scaffold and explanted ear were captured with a Vectra imaging system (Canfield Imaging Systems, Fairfield, NJ) and compared for changes in gross appearance. High-resolution CT scans were also taken of the scaffold and explanted ear. The titanium wire volume was segmented from the CT images and analyzed with CAD software. Overall changes in length, width, and thickness were measured, along with the overall curvature and local curvature profile of each section in the framework.

Results: Gross observation indicated good aesthetic appearance and flexibility. The explanted ear could be twisted and bent and is elastically deformable. Histologically, robust neocartilage formation was observed. 3D surface images were superimposed with depth differences colored in a scaled heat map (Fig. 1D). The central area of the ear (cavum of concha) decreased in depth, while the remainder of the structure stayed relatively unchanged. This observation was supported by dimensional measurements, which indicate that the depth decreases by 15.8%, with no significant changes in the overall length and width. Additionally, the overall curvature of the central area decreased by 11%. These changes are consistent with the compressive forces experienced by the scaffold during subcutaneous implantation. Local curvature analysis revealed that the greatest dimensional changes occur at the intersection points of the framework. This behavior is caused by sliding of the inner titanium wire within the outer coil sheath. The magnitude and direction of forces acting upon the wire framework were calculated from changes in curvature (Fig. 1E).

Conclusions: The composite ear scaffold maintained shape and size in an *in vivo* rat model, and supported the formation of flexible neocartilage. Surface imaging analysis revealed a decrease in overall depth due to compressive forces during implantation. Curvature analysis of the wire framework indicated sliding at intersection points, causing slight dimensional changes. Future iterations of the scaffold will focus on improved manufacturing processes, such as 3D printing, to correct these areas and enhance overall mechanical performance.

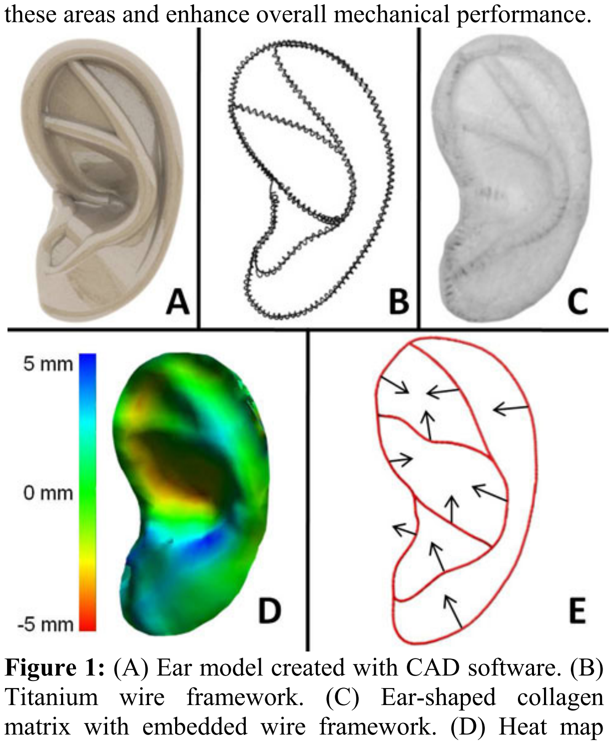

Figure 1: (A) Ear model created with CAD software. (B) Titanium wire framework. (C) Ear-shaped collagen matrix with embedded wire framework. (D) Heat map comparing differences in surface depth between scaffold and explanted ear. (E) Arrows representing the direction of forces exerted on the ear during implantation.