Narrative Review

Bio-Engineering in Microtia Reconstruction: A Narrative Review

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Abstract

Objective: To provide an overview of the role of 3D modeling and printing in reconstruction of congenital malformations of the ear by plastic surgeons.
Background: Three-dimensional (3D) modeling and printing have become widely adopted in surgical fields, whether it be for pre-operative planning, production of prosthesis, or outcomes monitoring. Plastic and reconstructive surgeons have shown interest in using 3D technology in craniofacial reconstruction, in particular for microtia.
Methods: A literature search was performed and identified articles using 3D modeling, printing and/or bioprinting for microtia reconstruction.
Discussion: In patients with unilateral microtia, 3D modeling and printing of the normal contralateral ear to be used as an intra-operative reference during costochondral or MedPor carving were preferred by surgeons to traditional 2D drawings. Three-dimensional models provided complex ear contour features, such as depth, and logistically saved time. In producing ear prostheses, the 3D technology improved surface texture and color match. Combining tissue engineering with 3D modeling and seeding chondrocytes onto a customized biodegradable ear framework is a promising avenue to restore aesthetics and to obviate certain challenges of autologous costochondral graft technique.
Conclusions and relevance: Microtia is a common congenital malformation and its current gold standard treatment presents with technical challenges. As medicine is becoming personalized, 3D modeling and printing will play a larger role in various surgical fields, including in microtia reconstruction. Future studies will likely focus on refining the acquisition of images to produce 3D models used as intra-operative references for carving, standardizing tissue engineering techniques and using bioprinting to produce external ears once the technology is clinically applicable.

Tags: 3D printing, Microtia, Bioprinting, Tissue engineering, Plastic Surgery

Background

Applications of three-dimensional (3D) modeling and printing have expanded in the recent years, now part of tissue and organ fabrication, implants and prostheses production, and various drug delivery systems, amongst others(1, 2). Developed in the 1980s, 3D printing consists of manufacturing objects based on digital reconstructions or models(3, 4).

With its increasing availability, the cost efficiency of 3D printing has improved for individualized small-scale production(3, 5, 6). Indeed, objects can be printed in a few hours only with high accuracy, reliability and repeatability(5, 6). In surgery, 3D printing allows for production of patient-tailored medical products and equipment, resulting in decreased operative time, shortened recovery, and improved overall surgical success(5, 6).

3D modeling and printing, has proved to be a promising tool for patients with microtia, a congenital malformation of the external ear within the first 6-8 weeks of gestation, secondary to teratogens, ischemia or genetic defects(7). It develops in 1 out of 5000 births(7). Defects of the auricle can range from a small concha with normal anatomy (grade 1), to severely deficient upper half with external auditory canal (EAC) possibly absent (grade 2), to small piece of remnant cartilage displaced upward and forward without EAC (grade 3) to anotia or complete absence of auricular tissue (grade 4) (7). In addition to the psychosocial issues resulting from having an abnormal ear, patients with microtia can develop impaired acoustic function resulting in suboptimal sound localization, speech perception and speech development(7). Current treatment options for microtia include the wear of an auricular prosthesis, the implantation of a synthetic ear-shaped framework or the graft of an autologous rib cartilage framework(8). The current gold standard treatment for microtia reconstruction consists of the latter. Following the Nagata method, in a two-step surgery, the surgeon carves the harvested rib cartilage into a shape similar to that of the normal contralateral ear and places it subcutaneously in a skin pocket where the ear should be(9, 10). The MedPor technique is an alternative using a pre-fabricated porous polyethylene implant(11). The implant is molded based off a template tracing of the contralateral ear for size, shape and projection. These current reconstructive techniques entail reproducing the complex 3D auricular contour and features with poor flexibility cartilage which is technically challenging and requires significant training. The complexity of microtia reconstruction can result in suboptimal esthetic results, justifying the need for a more accurate ear reconstruction technique. Surgeons and scientists have integrated 3D modeling and printing into their management of microtia. This narrative review discusses the most recent technological advances in synthetic and biologic microtia reconstruction techniques using 3D modeling and printing as published in clinical-scale studies.

Methods

A search of the current literature was conducted on PubMed from inception to January 2019 using the key terms “3D printing”, “microtia”, “3D modeling”. Studies were selected based on the relevance of the title and/or abstract of retrieved records. The initial screen excluded studies with irrelevant titles or abstracts. If content was unclear based from the abstract review in the initial screen, a formal article review was undertaken. Additional studies were identified from an extensive manual Internet search and from the reference list of relevant articles. Included studies were restricted to English and French. Articles assessed included reviews, case reports, prospective studies and experimental studies. Animal studies were excluded.

Discussion

3D printed model as intra-operative reference

In reconstructions where cartilage is needed, rib grafts are commonly harvested because of their abundant availability, evidence of durability, low infection rates and good cosmetic outcomes(12). Historically, multi-stage microtia reconstruction using autologous costochondral grafts was developed in the 1950s by Tanzer(13) and later modified and popularized by Brent(14), decreasing complication rates and improved esthetic results. Nagata later reduced the number of surgeries to 2 and set the basis of a four-level three-dimensional cartilage construct to give a more natural ear contour(15). This technique remains the gold standard today for microtia reconstruction with regards to long term safety and durability(7). The major difficulty is to sculpt the costal cartilage into a 3D cartilage framework, using a two-dimensional (2D) tracing of the normal contralateral ear as an intra-operative reference, to create an ear that is as symmetric as possible to the other in terms of size, projection and position. With this regard, two-dimensional (2D) tracings lack details of the complex ear contour features, but most importantly, they lack the depth and thickness components of the ear(16). Moreover, they entail constant back and forth movement between the carving set up and the patient, to further study the contralateral ear, which increases operative time and carries risks of infection(16, 17).

To overcome the shortcomings of 2D tracings, surgeons can use 3D printed digital models of the normal ear as an intra-operative reference tool when carving. By stacking a series of 2D X-Ray images, Computed Tomography (CT) can create 3D a geometric model of the patients' ear, but carries radiation exposure(18). In contrast, 3D surface imaging(16), 3D laser scanning(17), and 3D digital photography(19) are radiation-free methods that have been reported to construct digital models. They will be discussed here.

A group of plastic surgeons from South Korea used 3D laser scanning to create a mirror image of the patients' normal ear after it was casted using alginate(17). Once the 3D digital model was completed using computer-aided design (CAD) system, it was printed and used as an reference tool when carving the costochondral cartilage as per the Nagata method. Assessment of the accuracy of the shape, size and dimensions of the printed 3D ear model and the casted ear model resulted in a 2.31%. difference. Of note, an accuracy assessment was not performed between the casted ear model and the normal contralateral ear, as the children were too young to sit still during the 3D scanning process. Comparisons of the lateral view of the 3D ear model and the 2D template drawing of the normal ear produced by surgeons intra-operatively revealed a 16% difference. Although the time required to manufacture the 3D ear model was longer than that needed to draw the 2D template, the former was done pre-operatively. This allowed to reduce the intra-operative time by taking down the time required to draw the 2D template and the time allotted to back and forth movements between the carving set up and the patient. The authors did not specify how much time was saved. This study demonstrated the usefulness of 3D scan-to-print technology to create operative reference tools providing 3D anatomical details of the normal ear to simplify microtia reconstruction and to enhance the surgeon's intuition.

Similarly, a group of plastic surgeons from Taiwan and Singapore used 3D surface imaging to produce and print a 3D model of the normal ear used as a 3D intra-operative sculpting guide(16). Three-dimensional surface imaging generates a point cloud representation of the ear contour using x, y and z coordinates using stereophotogrammetry. The software used was previously validated with regards to the precision and geographic reliability of its anthropometric measurements of the auricle(20) as well as its safety and speed for quantification of craniofacial features(21). Using the MedPor technique, the authors found that obtaining 3D perceptions was critical in the framework fabrication. However, digital noise was found to obstruct part of the external ear contour.

In the United States, plastic surgeons have used 3D digital photography to generate a 3D geometric model of the unaffected ear(19). Once exported into a software, further sculpting and defining can add ultra-fine details and accentuate the essential landmarks of the ear contour. The digital model was 3D printed and brought into the operating theater as a reference when sculpting. In conjunction with the Nagata technique, using 3D digital photography allowed surgeons and engineers to digitally edit and print several models if refinement was necessary. The cost of production was estimated at 1$ for direct material and 500$ for personnel, which was cost-effective. This technique was found to decrease the degree of estimation required to shape the ear. Challenges remain to find the ideal software, digital preparation protocol, printer ink and device.

Auricle prostheses from 3D modeling

The complexity of microtia reconstruction is such that it can result in suboptimal esthetic results in patients subjected to multiple surgical procedures. Indeed, challenges of autologous reconstruction that are inherent to the patients' anatomy include insufficient soft tissue envelope, sub-optimal positioning of microtic remnants and the lack of a contralateral normal ear for guidance during reconstruction(22). Furthermore, complications of these types of procedures range from cartilage architectural collapse or implant extrusion, to donor site morbidity and asymmetric projection of the reconstructed ear. These are reasons why patients may turn to ear prostheses as an alternative. In the recent years, three-dimensional technology has been incorporated into anaplastology (the science of customizing facial, ocular or somatic prostheses) to recreate realistic human anatomy in previous microtia reconstruction with ear prostheses(23, 24). Using digital 3D modeling was found to ease the form, surface texture and color match of the prosthetic ear when compared with the normal contralateral ear, elements which are typically difficult to produce by maxillofacial prosthetists(23). In addition, using 3D technology reduces sculpting and clinic time(23). Weissler et al.(22) reported the case of a 13-year-old female with Treacher Collins Syndrome and bilateral microtia who failed multiple autologous reconstructions. A 3D surface laser scanner was used to generate a digital model of her father's ears (used to obtain a structural ear form given her complete absence of both ears), which was subsequently scaled, rotated and adjusted for esthetic proportions to the patient's reconstructed 3D craniofacial model. The 3D model was printed and modified by an anaplastologist to match the skin tone of the patient's auricular region. Intraoperative surgical navigation based off a 3D CT reconstruction of the ear region was found to facilitate precise and anatomically favorable alignment of the bone-anchored hearing aid (BAHA) implants drilling sites with the auricular prostheses(22). This improved ear position, projection and symmetry, key factors to achieve favorable esthetic outcomes(22). Limitations of using 3D technology to create prosthetic reconstructions included the costs of running and maintaining the hardware and software, as well as training technicians to use them(23).

Engineering patient-specific ear-shaped chondrocytes

Many steps in auricle cartilage bioengineering have consistently proven difficult. Finding an adequate cell source, both in terms of quality and quantity of cells, creating a 3-dimensional scaffold structure that yields minimal host immune reaction, seeding the latter with chondrocytes, and maintaining perfusion of the seeded scaffold are challenging(10). Many animal studies have been carried out to explore chondrogenesis capabilities and vascularization techniques(25-28). Recent developments in 3D printing and tissue engineering have made it possible for a group of Chinese scientists and plastic surgeons to successfully bioengineer patient-specific ear-shaped cartilage in patients with unilateral microtia of grade II or III(18). Pre-operatively, using CT, a 3D reconstruction of the normal contralateral ear was generated into a computer-aided design (CAD) system. Its digital mirror image was subsequently printed with a computer-aided manufacturing (CAM) system using resin. Molds of the 3D printed resin ear were then created to help produce a biodegradable scaffold made of polycaprolactone (PCL), polyglycolic acid (PGA) and polyactic acid (PLA). Through a biopsy, the cartilage remaining in the microtic ear was retrieved and further grown in vitro onto the above-described scaffold. Remnants of cartilage found in microtic ears have been deemed an adequate cell source for tissue engineering because of its morphological, architectural and biochemical properties(10). A 3D laser scanning system was employed to obtain a 3D model of the cartilaginous graft after 12 weeks of in-vitro growth to compare its shape to that of the initial ear-shaped scaffold (before cell implantation). The cartilaginous graft was later implanted into a tissue-expanded skin envelope overlying the normal auricular region in the recruited patients. By combining CT scan reconstructions, CAD-CAM systems, and 3D-printing, these researchers have successfully engineered patient-specific ear constructs to a degree of similarity that cannot always be achieved with autologous reconstruction. Furthermore, using the above-mentioned 3D technologies allowed to provide the ear scaffold with the mechanical support and strength necessary to maintain its 3D structure after implantation under skin tension. Limitations included the radiation exposure from using CT scan to acquire images for 3D modeling of the contralateral ear. This biological technique appears promising for microtia reconstruction, but longer follow-up is needed for this clinical trial to assess graft extrusion, shape and mechanical properties, as patients involved in the study were only followed for 2.5 years. Furthermore, when compared to synthetic implants, biological constructs of the ear cartilage framework require significantly more time (12 weeks) as well as additional surgeries, as it is a minimum two-step surgery. The costs of production were not disclosed by the authors.

Conclusion

Plastic surgeons are showing tremendous interest in using new technologies to achieve ideal reconstructions. Microtia is a common anomaly that results in significant functional and aesthetic impairments. As medicine is moving towards personalized medicine, three-dimensional modeling and printing will continue to expand frontiers of pre-surgical design. Adopting the 3D technology to create individualized auricular constructs can obviate the intrinsic differences in auricular shape, implant properties, recipient tissue condition and surgical techniques, elements which all contribute to the unpredictability of the final aesthetic and functional outcomes of microtia reconstruction. In addition to techniques described in this article, further applications of 3D modeling and printing could include customizing MedPor implants. Indeed, using 3D scanning and printing techniques could increase the reconstructed ear’s similarity with the native, in unilateral microtia. Bioprinting tissue and organs directly from living cells has the potential to minimize the host immune response and to allow for a more precise control of speed, resolution, volume and diameter of the final product. However, as bioprinting is an idea in its infancy still far from applicability, 3D modeling and printing for microtia reconstruction will likely focus on producing intra-operative references for costochondral carving.

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