Three-Dimensional Printing - A Boon for Maxillofacial Surgeons

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Abstract

The head and neck region are comprised several vital structures which are protected inside the bony cavities. The anatomy of these structures is also very complex and recreating these structures following trauma or pathology can be taxing. Several advancements have taken place in this field and three-dimensional (3-D) printing is one of the emerging techniques with a promising future, especially in field of maxillofacial surgery. 3-D printing is a method of manufacturing in which various materials (metal, plastic, etc.) are deposited onto one another in layers to produce a 3-D object that can be used as a customized replacement of missing tissue or organ, or for treatment planning. Here we have enumerated the application of 3-D printing in the field of maxillofacial surgery, the various techniques, procedure, and materials available in a concise manner and allow us to peak into the future application of this newer technology.

Keywords: Three-dimensional printing, Maxillofacial reconstruction, Customized implants, Three-dimensional printed guides, Three-dimensional printed splints, Virtual maxillofacial surgeries.

Introduction

Large bony defects may result from trauma, space occupying lesions and infections in the craniofacial region which results in the patient being functionally and aesthetically compromised. Reconstructive surgeries can be extremely challenging even to the most experienced surgeon especially due to complex anatomy, sensitivity of the involved systems, and uniqueness of each defect.[1] Autogenous graft still remains the gold standard for reconstructing such defects, but it also comes with the added complication of creating a secondary wound in the donor site and the hassle of harvesting the graft.

Over the past several decades several alloplastic materials have been introduced in the field of medicine which is being utilized to treat such defects. With larger defects, often the reconstruction has to be made by preserved allogenous bone material or other 18 material, as not enough autogenous material is available.[2] To overcome these concerns, several alloplastic materials, such as metals, plastics, ceramics, and composites, are used for the reconstruction of skull bone defects. Patient specific implant is an effective solution where fit has to be precise for the anatomical defects or malformations. The technologies, such as additive manufacturing (AM) also known as rapid prototyping (RP) or three-dimensional (3D) printing, are robustly growing and have positively influenced the biomedical sector over the last decade allowing the surgeons and researchers to utilize them in manufacturing objects.[3,4]

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As no two cases are the same these prefabricated mass manufactured implants might not to be suitable for types of defects. There's an increasing need to customize the implants to cater to a particular case and that's when 3-D printing comes into the picture.[5] 3-D modeling works by building a model from the ground up, depositing the material to be used in a layer-by-layer manner using digitally controlled and operated material laying tools. The 3-D modeling has the capacity to create exact models of a patient's anatomic deformity and serve as an indispensable tool when educating patients. When patients can use their sense of touch to hold a printed model and compare it with a model of their postoperative outcome, they can more realistically manage their expectation.[6] This systematic review aims to summarize the current published literature and known ongoing research on 3-D printing in oral and maxillofacial surgery. This article reviews the trends and advances of 3-D printing and its impact on maxillofacial surgeries.

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History

3-D printing is not a very recent invention, as depicted in Figure 1. In fact, the first ever 3-D model was built in 1981 by Hideo Kodama in Nagoya Municipal Industrial Research Institute by using photopolymers. Then in 1984, Charles Hull invented stereolithography (SL), i.e., process of building 3-D models using digital data. Then in 1992, the world's first stereolithographic apparatus (SLA) machine was built, which made it possible to build complex parts, layer by layer; along with the world's first selective laser sintering (SLS) machine, which could shoot laser at a powder instead of photopolymer liquid. In 1999, the world's first 3-D printed organ was transplanted in humans, when scientists at wake forest institute for regenerative medicine 3-D printed synthetic scaffolds of a human bladder and coated them with human cells. The newly formed tissue was then transplanted into patients, with no rejections as the organ was made of their own cells.[7] Of various medical fields, craniofacial plastic surgery is one of the areas that pioneered the use of the 3D printing concept and is most promising. RP technology was introduced in the 1990s to medicine. Medical modeling in craniofacial surgery based on 3D printing has mainly been developed over the last 15 years. Computer-aided design-computer aided manufacturing (CAD-CAM) was first introduced to fabricate craniofacial anatomical models based on images from CT in 1987.[8] A 3-D printed model was used by Bill *et al.* for planning of a surgery, in which an allogenic bone transplant was used for cranioplasty. The recent most advancement includes 3-D bioprinting, which is the technique used for sequencing of biological materials like various cells and biomolecules and fabricating tissue-like constructs and is witnessing rise day by day, with the use of advanced AM technology.

Current Trends in 3-D Printing Techniques Used in Craniofacial Surgery

3-D printing technology can be classified by the techniques, the materials or aimed deposition process.

The technical type of classification includes:
(1) SL
(2) The SLS
(3) 3-D printing (binder-jet), fused deposition modeling (FDM)
(4) Direct metal laser sintering
(5) Laminated object manufacturing
(6) Electron beam melting;

The material classification includes thermoplastic, metal powder, ceramic powder, eutectic metals, alloy metal, photopolymer, paper, foil, plastic film, and titanium alloys [depicted in Table 1]; the aimed deposition process classification includes PolyJet modeling based on drop-on-drop deposition, and FDM based on continuous deposition. The most frequently used methods are reviewed in Table 1. For medical usage, after the computed tomography (CT) scan, the rendering of the DICOM data and transformation into SL data files takes a maximum of 30 min. In general, 3D printer accuracy would depend on the accuracy of CT scans, especially of which thickness should be as thin as possible (1 to 2 mm is a good compromise for a skull study).[9]

Process of 3-D Printing

The process of 3D printing in oral and maxillofacial surgery starts with anatomical scans using various imaging techniques such as magnetic resonance imaging (MRI) and computed tomography (CT) scans and cone bean CT (CBCT) to acquire images for 3-D printing of objects. The images are then transferred into a modeling software that processes them into positive-space models representing the actual hard-tissue anatomy or negative-space models representing the intervening space next to the positive space. Many modeling software are now available in the market such as Mimics, Amira, Rhino, SurgiCase, ITK-Snap, InVesalius, and 3D Slicer. Of these, Mimics (Materialize NV, Leuven, Belgium) is one of the most commonly used software.[10] With the help of CAD software will create a virtual 3D prototype with Standard Tessellation Language (STL) format to allow 3D printing. The product of the modeling software is then converted to the printing software. Commonly used printing software is 3D Systems (Rock Hill, South Carolina, USA), SolidWorks and Alaris.[10] The printers used are laser-based printers, inkjet printers or

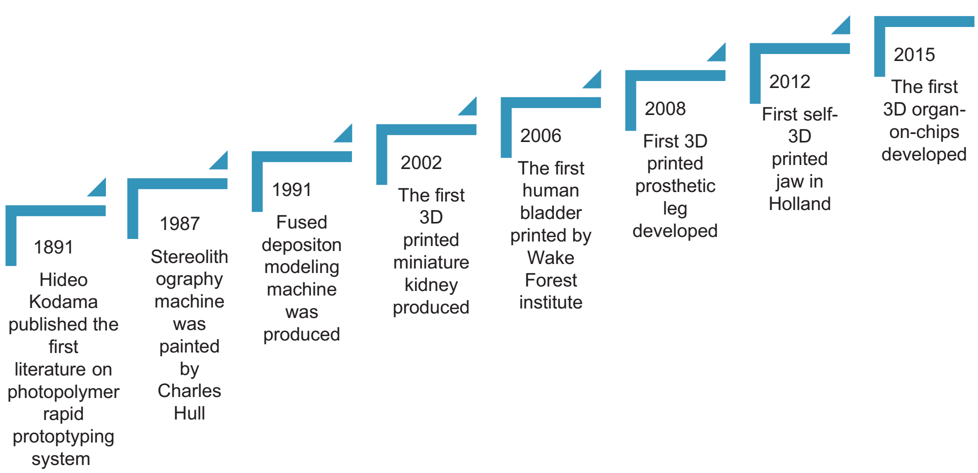

Figure 1: Chart depicting evolution of three-dimensional printing in medicine

Table 1: Types of materials and processes used in three-dimensional printing

Three-dimensional printing technology	Material	Aimed deposition process	mechanism
Liquid base • Stereolithography • PolyJet or multijet printing	Photopolymer Acrylonitrile butadiene styrene (ABS) acryl	Drop on drop deposition	Layer by layer curing method based on ultraviolet (UV) laser focusing on photosensitive polymer Printer head that extrude the liquid resin and wax with UV laser.
Powder base • Selective laser sintering • 3-D printing • Direct metal laser sintering • Electron beam melting	Thermoplastic Metal powder Plastic powder Alloy metal Ceramic powder Titanium alloys	Drop on powder deposition	
Solid base • Fused deposition modeling • Laminated object manufacturing	Thermoplastic Eutectic metals ABS Paper Foil Plastic film	Continuous deposition	

micro extrusion printers. The printing then happens in the X, Y, and Z-axis in a layer-by-layer manner to obtain the final product. Depending on the application, appropriate printing technique is selected, for example, FDM, SL (SLA), SLS, inkjet bioprinting, extrusion bioprinting, and laser-assisted bioprinting.[11] Finally, the printed object will go through a post-printing modification to obtain the final printed object (Figure 2).

Classification of Application of 3-D Printing

Three-dimensional printing technology in craniomaxillofacial surgery can be classified into contour models (type I), guides (type II), splints (type III), and implants (type IV). These four methods vary in their use between craniofacial and maxillofacial surgery, reflecting their different goals.[12]

(1) Contour model - These models can be utilized in almost any surgery where greater visualization is needed, precision is necessary for appropriate alignment, and where having an intraoperative model reveals hidden anatomy of the patient. This is especially useful in the pediatric population with their finer anatomy and limited incisions.[12]

(2) Guides - Bone defects such found in skulls, orbits, and zygomas have the best application here. The image is captured, the DICOM file is converted to an STL file, and then software allows us to capture the negative space to make a guide. These guides can also be used in real-time in the surgical field to counter the challenges otherwise posed.

(3) Splints - One of the most common applications of splints is for jaw surgeries, especially orthognathic surgery to correct underbite or overbite, thus, very commonly used in patients with cleft lip and cleft palate. Virtual surgeries can be easily performed using specialized software which was earlier performed only by caste models and such.

(4) Implants - This is the least common type of 3D printed object, in part because of the manufacturing sophistication necessary to 3DP biocompatible implantable materials such as porous polyethylene[13] (such as Medpor from Stryker), polyetheretherketone (PEEK from DePuy Synthes), or in the future other biocompatible or even bioengineered implants. The other significant hurdle is the regulatory concern, which is sensible given that these implants are replacing tissues when there are no other good autologous reconstructive options available, such as a child with small anatomy and therefore limited donor

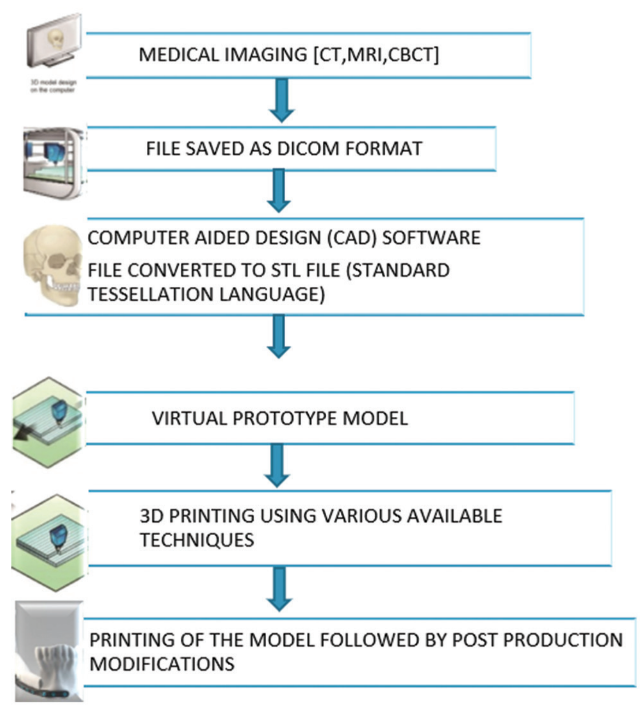

Figure 2: Steps of three-dimensional printing

Table 2: Specific applications of three-dimensional printing in maxillofacial surgeries

Category	Specific surgeries
Mandibular surgeries	Mandible reconstruction
	Mandible resection
	Bilateral sagittal split osteotomy
	Bilateral intraoral vertical ramus osteotomy
	Osteoradionecrosis
	Mandibular angle ostectomy
	Condylar head reconstruction
	TMJ implants
Maxillary surgeries	Reconstruction
	Orthognathic surgeries
Orbital surgeries	Orbital fractures
	Hypertelorism correction
	Orbital reconstruction
Nasal surgeries	Nasal reconstruction
	Nasal prosthesis retention
Cranial surgeries	Cranioplasty
	Cranial vault reconstruction
	Craniosynostosis surgery
	Cranial defects
Others	Frontal sinus reconstruction
	Midface reconstruction
	Midface osteotomies
	Fracture visualization
	Hardware placement: Plates and screws
	Dental implants
	Cleft lip-nose-palate
	Ear reconstruction

sites. Therefore, currently most hospital 3D printers would not be able to do this.

Applications of 3-D Printing in Craniomaxillofacial Surgeries

The surgical application of this technology can be focused on four different aspects:

1. Obtaining highly accurate anatomic prototype models to ease preoperative planning and improve postoperative facial contour symmetry, for example, reconstruction of the mandible, the maxilla, and the orbits.[14,15] This may help clinicians to inspect anatomy preoperatively, practice different techniques, and consequently reduce the operating time and minimize errors.[16]
2. Virtually planning and printing pre-contoured grafts and plates to improve surgical outcomes and reduce operating time.[17,18]
3. Offering high-accuracy prostheses that can enhance the aesthetic and psychological status of patients suffering from significant scarring, deformation, and asymmetry.[19,20]
4. Proposing cutting-edge simulation models to enhance surgical education at both undergraduate and postgraduate level.[21]

3-D printing enables the surgeon to recreate extremely precise models which in turn eases the pre-operative planning and post-operative results as it gives more insight into the complex anatomic structures which might not always be appreciated in a conventional CT or MRI. 3D printing can be used to study the bony defects which are left behind after surgical resection. Custom made plates give better results compared to standard pre-fabricated plates. The pre-contoured, custom-made titanium plates can also be used to guide the osteotomies for the fibular flap and for segmental modeling of the fibular flap to the plate when it is being raised.[17] Individualized orbital implants, particularly CAD-based ones, allow a more precise posttraumatic orbital reconstruction than standard preformed implants. Various applications of 3D printing that are specific to maxillofacial surgeries are mentioned in Table 2. The same effect was observed for the use of intraoperative navigation.[13] This technology can also be used to simulate the complex anatomy and it serves as hands-on aid for practicing surgeries without jeopardizing patients health. Various applications in maxillofacial surgery are given in Table 2.

Conclusion

The introduction of AM in the field of surgery is nothing short of a blessing as recreating the complex craniofacial structures is a time taking and technique sensitive task. After reviewing the existing literature its evident that most authors settle on the fact that 3-D printing aids in creating study models which can be used for demonstration purposes as well as for simulating surgeries which is an excellent adjuvant for the surgeon to pre plan the procedure. The use of this technology not only decreases the intra-operative time but also delivers superior results postoperatively. Several factors that are presently posing a challenge to widespread usage of 3-D printing are the software being used, the type of printing device, the extent of accuracy, type of printing material being used, the production time, the human efficiency, technique sensitivity, and overall cost. As the entire process of 3-D printing needs sophisticated software and tools, cost becomes a crucial factor. This technology is still a work in progress and with it comes its own pros and cons. There is much more to look forward to in future applications of this technology. And see how further, it can evolve and its implications on treating various surgical cases in maxillofacial surgery.

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