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Three-Dimensional Printing: A Novel Technology for Use in Oral and Maxillofacial Operations

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Additional information is available at the end of the chapter

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Abstract

Three-dimensional (3D) printing is cited as “a novel, fascinating, future builder technology” in many papers and articles. Use of this technology in the field of medicine and especially oral and maxillofacial surgery is expanding. The type of manufacturing systems, materials, cost-effectiveness, and also bio-printing, with studies from around the world today, make this field a “hot-topic” in reconstructive and regenerative surgery. This chapter evaluates the latest updates and scientific uses of 3D printing.

Keywords: Rapid prototyping, three-dimensional printing, reconstructive surgery, oral, maxillofacial surgery

1. Introduction

Three-dimensional printing (3D), also known as rapid prototyping (RP), was first introduced in the 1980s. During the past three decades, enormous changes and developments have been made by scientists modifying this technology, materials, and accuracy. Within the field of craniofacial surgery, 3D surgical models have been used as templates to harvest bone grafts, tailoring bioprosthetic implants, plate bending, cutting guides for osteotomies, and intraoperative oral splints. Using 3D models and guides has been shown to shorten the operative time and reduce the complications associated with it. The ultimate goal of any surgical procedure is to improve peri-operative form and function and to minimize operative and postoperative morbidity. Many exciting and new technological advances have opened a new

era in the field of oral and maxillofacial surgery over the last years, and 3D printing is among the most novel. The aim of this chapter is to introduce 3D printing method and its role in contemporary oral and maxillofacial surgery and to review different applications and benefits of 3D printing-assisted surgeries in the oral and maxillofacial region.

2. History and benefits

Three-dimensional printing has been utilized in diverse aspects of manufacturing to produce different objects from guns, boats, and food to models of unborn babies. From over 1450 articles related to 3D printing listed in PubMed, nearly a third of them were published in the last 2 years [1].

3D printing is a manufacturing process wherein objects are fabricated in a layering method during fusing or depositing different materials such as plastic, metal, ceramics, powders, liquids, or even living cells to build a 3D structure [2, 3]. It is a process of generating physical models from digital layouts [4, 5]. This technology demonstrates a technique where a product designed via a computer-aided scheme is manufactured in a layer-by-layer system [6]. This process is also known as RP, solid freeform technology (SFF), or additive manufacturing (AM) [7].

3D printing techniques are not new and have existed since 30 years ago [8–10]. This technology was first introduced and invented by Charles Hull in 1986, and at first it was utilized in the engineering and automobile industry for manufacturing polyurethane frameworks for different models, pieces, and instruments [11]. Originally, Hull employed the phrase “Stereolithography” in his US Patent 4,575,330, termed “Apparatus for Production of Three – Dimensional Objects by Stereolithography” published in 1986. Stereolithography (SL) technique included subjoining layers over the top of each other, by curing photopolymers with UV lasers [12, 13].

Since then, 3D models have been used for a diversity of different objectives. Since 1986, this process has started to accelerate and has honored recognition globally and has influenced different arenas, such as medicine. The developing agora for 3D desktop printers encourages wide-ranging experimentations in all fields. Generally, medical indications of these printers are treatment planning, prosthesis implant fabrications, medical training, and other usages [4]. Having being used in the military, food industry, and arts, RP has received much attention in the field of surgery in the last 10 years [6, 14]. The pioneering usage of SL in oral and maxillofacial surgery was by Brix and Lambrecht in 1985. Later, this technique was used by them for treatment planning in craniofacial surgery [15]. In 1990, SL was used by Mankovich et al. for treating patients having craniofacial deformities [16, 17]. They used it to simulate bony anatomy of the cranium using computed tomography (CT) with complete internal components [17, 18].

By aiding in complex craniofacial reconstructions, 3D printing has recently earned reputation in medicine and surgical fields [19–21]. Today, maxillofacial surgery can benefit from additive

manufacturing in various aspects and different clinical cases [22]. This technique can help with bending plates, manufacturing templates for bone grafts, tailoring implants, osteotomy guides, and intraoperative occlusal splints [23–27]. RP can shorten surgery duration and simplify pre- and intraoperative decisions. It has enhanced efficacy and preciseness of surgeries (**Table 1**) [10].

Diagnosis and treatment planning
Direct visualization of anatomic structures
Surgical guides/templates
Surgical practice/rehearsal
Designing incisions
Surgical resections
Assessment of bony defects for grafting
Adaptation/pre-bending of reconstruction plates
Fabrication of custom prostheses
TMJ prostheses, distraction devices, fixation devices
Decreased surgical time, anesthesia time, wound exposure duration
More predictable results
Improved colleague communication
Educational tool for patients

Table 1. Uses of 3D models [22].

3. Manufacturing process and types of models

There are different technologies introduced for 3D printing. Binder jetting (BJ), electron beam melting (EBM), fused deposition modeling (FDM), indirect processes, laser melting (LM), laser sintering (LS), material jetting (MJ), photopolymer jetting (PJ), and SL are well-known technologies of 3D printing [14, 28, 29]. There are many different 3D printing techniques. Benefits and disadvantages are factors inherent to each technology system [14]. Among this variety of different techniques, there is a huge demand for oral and maxillofacial surgery for SL, FDM, and PJ [1, 28, 30]. **Table 2** summarizes some different three-dimensional printing technologies.

3.1. Stereolithography (SL)

The initial 3D printing technique SL began in the late 1980s [31]. The original SL uses a laser beam for resin polymerization in two-dimensional patterns [32]. Being the pioneering additive manufacturing method, SL produces 3D objects by curing layers of liquid photopolymer or

epoxy resin with a low-power UV laser [13]. SL projects a UV laser to a cross section of a single layer of the resin onto a photopolymer resulting in the setting of the layer. This is repeated until fabricating all zones of the product [1]. This technique utilizes a mirror to guide the laser to the surface in a layer-by-layer manner. Furthermore, the 3D device projects it on the surface resins. This procedure is done from the base to the surface (**Figure 1**) [14, 33].

Techniques	Advantages	Disadvantages
Light cured resin		
1. Stereolithography (SL) —Light-sensitive polymer cured layer by layer by a scanning laser in a vat of liquid polymer	Rapid fabrication. Able to create complex shapes with high feature resolution. Lower cost materials if used in bulk	Only available with light curable liquid polymers. Support materials must be removed. Resin is messy and can cause skin sensitization and may be irritant by contact and inhalation. Limited shelf life and vat life. Cannot be heat sterilized. High-cost technology
2. Photojet—Light-sensitive polymer is jetted onto a build platform from an inkjet-type print head and cured layer by layer on an incrementally descending platform	Relatively fast. High-resolution, high-quality finish possible. Multiple materials are available with various colors and physical properties including elastic materials. Lower cost technology	Tenacious support material can be difficult to remove completely. Support material may cause skin irritation. Cannot be heat sterilized. High- cost materials
3. DLP (digital light processing)—Liquid resin is cured layer by layer by a projector light source. The object is built upside down on an incrementally elevating platform	Good accuracy, smooth surfaces, relatively fast. Lower cost technology	Light curable liquid polymers and wax-like materials for casting. Support materials must be removed. Resins are messy, can cause skin sensitization, and may be irritant by contact. Limited shelf life and vat life. Cannot be heat sterilized. Higher cost materials
Powder binder		
Plaster or cementaceous material set by drops of (colored) water from “inkjet” print head. Object built layer by layer in a powder bed, on an incrementally descending platform	Lower cost materials and technology. Can print in color. Unset material provides support. Relatively fast process. Safe materials	Low resolution. Messy powder. Low strength. Cannot be soaked or heat sterilized
Sintered powder		
Selective laser sintering (SLS) for polymers —Object built layer by layer in powder bed. Heated build chamber raises temperature of material to just below melting point. Scanning laser then sinters powder layer by layer in a descending bed	Range of polymeric materials including nylon, elastomers, and composites. Strong and accurate parts. Self-supported process. Polymeric materials—commonly nylon may be autoclaved. Printed object may	Significant infrastructure required, e.g., compressed air, climate control. Messy powders. Lower cost in bulk. Inhalation risk. High-cost technology. Rough surface

Techniques	Advantages	Disadvantages
	have full mechanical functionality. Lower cost materials if used in large volume	
Selective laser sintering (SLS) — for metals and metal alloys. Also described as selective laser melting (SLM) or direct metal laser sintering (DMLS). Scanning laser sinters metal powder layer by layer in a cold build chamber as the build platform descends. Support structure used to tether objects to build platform	High-strength objects can control porosity. Variety of materials including titanium, titanium alloys, cobalt chrome, stainless steel. Metal alloy may be recycled. Fine detail possible	Elaborate infrastructure requirements. Extremely costly technology. Moderately costly materials. Dust and nanoparticle condensate may be hazardous to health. Explosive risk. Rough surface. Elaborate post-processing is required: Heat treatment to relieve internal stresses in printed objects. Hard to remove support materials. Relatively slow process
Electron beam melting (EBM, Arcam). Heated build chamber. Powder sintered layer by layer by scanning electron beam on descending build platform	High-temperature process, so no support or heat treatment needed afterward. High speed. Dense parts with controlled porosity	Extremely costly technology moderately costly materials. Dust may be hazardous to health. Explosive risk. Rough surface. Less post -processing required. Lower resolution
	Thermoplastic	
Fused deposition modeling (FDM) First 3DP technology, most used in “home” printers. Thermoplastic material extruded through nozzle onto build platform	High porosity. Variable mechanical strength. Low-to-mid-range cost materials and equipment . Low accuracy in low-cost equipment. Some materials may be heat sterilized	Low cost but limited materials— only thermoplastics. Limited shape complexity for biological materials. Support material must be removed

Table 2. 3D printing modalities and materials [14].

It is necessary to extract waste materials manually from the eventual outcome [34–36]. Nowadays, SL is known as the gold standard in 3D manufacturing with yield resolutions up to 0.025 mm. SL is reliable in reconstruction of internal frameworks and is more efficient in fabricating larger objects [37]. SL is largely accepted to have the best surfacing and the most accuracy of any 3D technology. Materials used in this system must be to some degree brittle and light [38, 39]. Acrylics and epoxies are commonly used for this method [40]. However, SL still requires manual handling after fabrication, and the process lasts more than a day to be completed. SL is more expensive than other techniques due to materials used, and the printer is considered more expensive due to the high cost of the raw materials and device maintenance [23, 41]. SL is largely utilized for producing implant drill guides [14]. The ability to build complex and detailed structures, extraction of waste resin without difficulty, and extremely high resolution (~1.2 um) are considered main advantages of SL [42] feature.

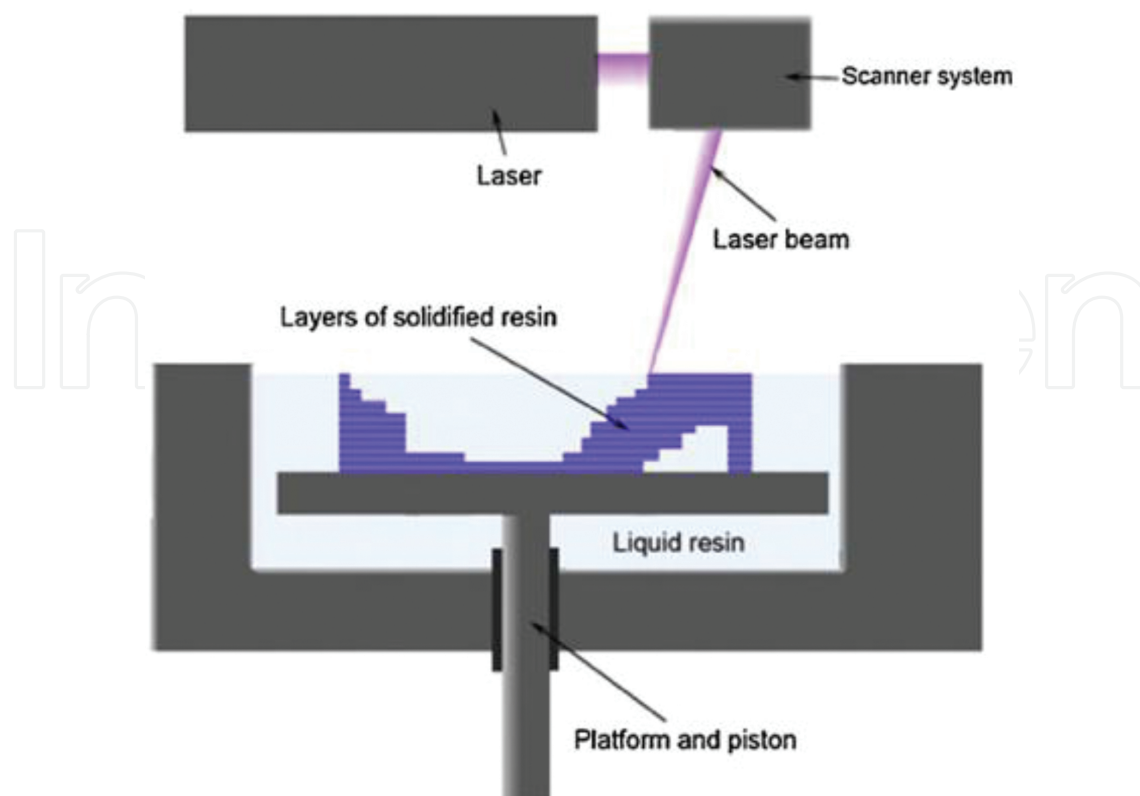


Figure 1. Schematic view of SL [115].

3.2. Fused deposition modeling

FDM uses a similar principle to SL in that it builds models on a layer-by-layer basis. When there is a discussion about cost-effectiveness, FDM is considered among the most utilized consumer 3D printing methods [16, 43, 44]. In FDM, a melted filament of thermoplastic material is extruded from a nozzle moving in the x-y plane and solidifies upon deposition on a build plate [45]. The build plate is lowered by 0.1 mm after each layer reappears. The process is repeated until the final product is produced. The most frequently used raw materials in FDM printers are acrylonitrile-butadiene-styrene (ABS) and polylactic acid (PLA) materials known for being key components of scaffold structures used for “bioprinting” [40].

Notable disadvantage and shortcoming for FDM is disability to form complex structures and most anatomical structures with complex shapes. For manufacturing a clean product, hollow internal structures or blind-ended openings are especially troublesome. Almost all household FDM printers are currently limited in mono-color and mono-material for manufacturing. However, this can be overcome by recently developed dual-extruder technology. In this technology, two filaments of different colors or materials can be extruded from a common printer head. MakerBot Replicator 2X Experimental (MakerBot Industries, New York, NY, USA), Cube 3 (3D Systems, Rock Hill, SC, USA), and Creatr x1 (Leapfrog, Emeryville, CA, USA) are known for this ability. Even more, the second extruder can be configured to build

support structures using MakerBot Dissolvable Filament (MakerBot Industries), made of high-impact polystyrene (HIPS) [6, 46].

Support structures are required for FDM models such as SL as thermoplastic needs time to harden and also the layers to bond together [47]. Since multiple extrusion nozzles can be used in FDM, each with a different material, there is no theoretical restriction on compositional gradients in all three dimensions for FDM. High porosity due to the laydown pattern and good mechanical strength are notable and key advantages of FDM (**Figure 2**).

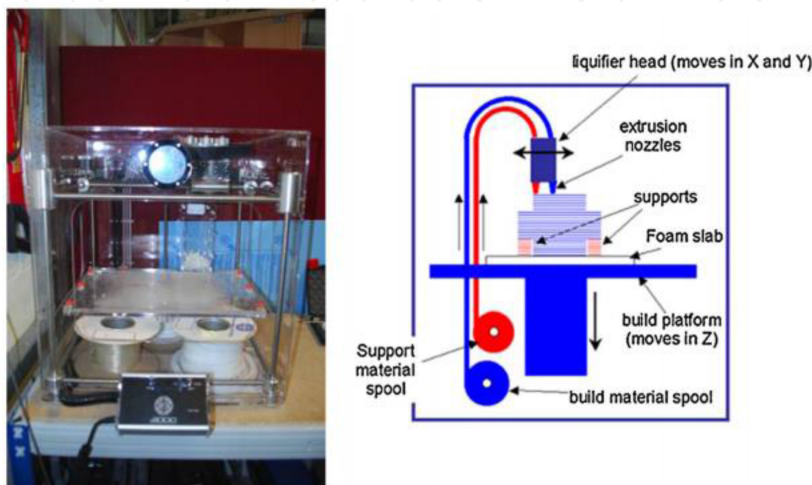


Figure 2. Schematic view of FDM [40].

3.3. PolyJet modeling

Multijet modeling printing, also known as MultiJet Printing (3D Systems, Rock Hill, SC, USA) or PolyJet Technology (Stratasys, Edina, MN, USA), is similar to SL; the difference is that the liquid photopolymer is immediately cured by UV light [48]. Multijet modeling printing can manufacture prototypes with high resolution (16 μ) that is comparable to or even better than SL. The advantage is the capacity to print in multiple materials for the desired degree of tensile strength and durability. An MJM printer is easier to maintain than an SL system. On the contrary, a disadvantage is the high price of these printers which makes MJM(Multi Jet Modeling) more suitable for large-scale productions rather than for office-based applications (**Figure 3**) [6].

The drawback is that the equipment and materials are costly to purchase and run, and the support materials can be tenacious and rather unpleasant to remove. They are useful for printing dental or anatomical study models, but these are expensive when produced. A particular advantage of this technology is that the use of multiple print heads allows simultaneous printing with different materials, and graduated mixtures of materials, makes it possible to vary the properties of the printed object, which may for example have flexible and rigid parts, for the production of indirect orthodontic bracket splints [14].

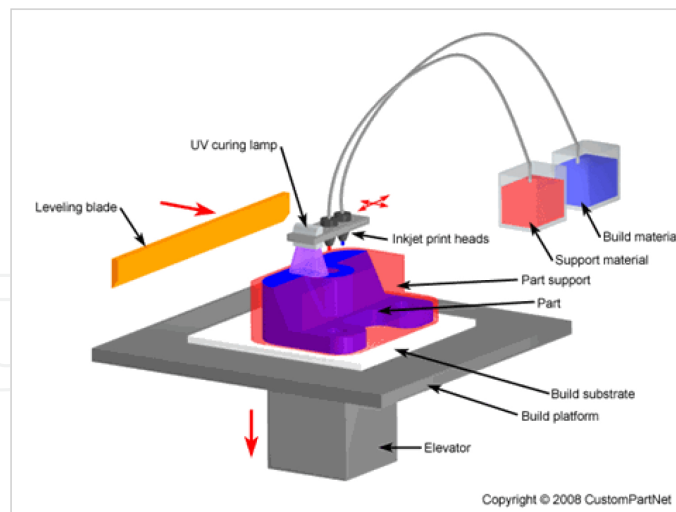


Figure 3. Schematic view of PolyJet [116].

4. Accuracy of 3D printing

Additive manufacturing plays a critical role in craniomaxillofacial surgery [49].

3D models simulate anatomy of the human body and can be extensively useful in oral and maxillofacial surgery. These models are of great value in decision making [50]. 3D models must be precise and extremely accurate in simulating head and neck anatomy to be beneficial in maxillofacial surgery. Faulty and inexact models can jeopardize diagnosis and treatment planning [16, 51]. There is limited data available about evaluation of the accuracy of 3D printed models. Inaccurate models can cause dramatic errors in treatment planning and simulations [49]. 3D printer accuracy generally depends on the accuracy of CT scans. CT is modality of choice for 3D printing purposes. While obtaining CT images, each slice thickness must be as thin as possible (1–2 mm) [30]. At present, no gold standard is introduced for measuring the accuracy of medical 3D models [49]. The accuracy of different additive manufacturing technologies is examined by researchers in maxillofacial surgery globally. The literature indicates that different techniques have different accuracy levels in reconstructing maxillofacial structures using 3D printing. As mentioned before, experiences have pointed out that SL creates 3D models with great accuracy. Average deviation of SL models varies from 0.20–0.85 mm. Error percentage in these models is between 0.6 and 6% [17, 30, 52–54]. Peter Shih-Hsin Chang et al. investigated the accuracy of SL for modeling midface irregularities. This was done comparing distances between key landmarks on the skulls and 3D models. Average overall difference between replicas and cadaver samples was between 0.8 and 2.5 mm in all locations. They stated that SL preciseness is affected by variants in different stages of manufacturing such as data collection and transfer, product fabrication, and maintenance [38]. Preciseness and accuracy is critical in orthognathic surgery for gaining better results both esthetically and functionally. In a recent study, Shqaidet et al. evaluated the accuracy of 3D printed wafers of 10 orthognathic patients. After aligning with dental models, the absolute mean error of the

wafers was 0.94 (0.09) mm. In this research, they showed error in 3D printed models is up to 1.73 mm which is considerable and will distort skeletal movements [55]. In another study, the PolyJet technique had the most precise fabrication in simulating mandibular architecture [50].

Salmi et al. assessed the accuracy of different 3D printing techniques by measuring balls attached to each 3D model. It was concluded that the PolyJet technique had the least inaccuracies [49].

Table 3 demonstrates results of different studies with accuracy measurement of 3D printed models.

Authors	Comparisons	Mean difference (%)	Measuring equipment
Salmi et al. (2013)	SLS e 3D CT (original 1. & 2. model) 3DP e 3D CT (original 1. & 2. measurement) 3DP e 3D CT (moderate) 3DP e 3D CT (worse) PolyJet e 3D CT (original 1. & 2. measurement)	0.79 0.26 & 0.80 0.32 0.67 0.43 & 0.69 0.44 0.38 0.22 0.55 0.37 0.18 0.12 & 0.18 0.13	Coordinate measuring machine and measuring balls & Pro Engineer software for 3D models
El-Katatny et al. (2010)	FDM e 3D CT skull FDM e 3D CT mandible	0.24 0.16 0.22 0.11	Digital caliper
Ibrahim et al. (2009)	SLS e dry mandible 3DP e dry mandible PolyJet e dry mandible	1.79 3.14 2.14	Digital caliper and test indicator attached to electric milling machine
Silva et al. (2008)	SLS e dry skull 3DP e dry skull	2.1 0.2 6.7	Digital caliper
Nizam et al. (2006)	SL e dry skull	0.08 1.25	Digital caliper
Chang et al. (2003)	3DP e fresh skull	2.1 e 4.7	Dial caliper
Choi et al. (2002)	SL e dry skull SL e 3D CT skull	0.56 0.39 0.82 0.52	Caliper & Magicview Software for 3D model
Asaumi et al. (2001)	3D CT e dry skull SL e dry skull	2.1 6.0 6.3	Caliper & 3D CT images
Berry et al. (1997)	SLS e 3D CT	0.64	None reported
Barker et al. (1994)	SL e dry skull	0.6 e 3.6	
Ono et al. (1994)	SL e dry skull	3	
Waitzman et al. (1992)	3D CT e dry skull	0.9 (0.1 e 3.0)	CT images & caliper
Dawood, A., B. M. Marti, V. Sauret-Jackson and A. Darwood (2015). "3D printing in dentistry." <i>British dental journal</i> 219 (11): 521-529.			
Mehra, P., J. Miner, R. D'Innocenzo and M. Nadershah (2011). "Use of 3-d stereolithographic models in oral and maxillofacial surgery." <i>Journal of maxillofacial and oral surgery</i> 10 (1): 6-13.			
Salmi, M., K.-S. Paloheimo, J. Tuomi, J. Wolff and A. Mäkitie (2013). "Accuracy of medical models made by additive manufacturing (rapid manufacturing)." <i>Journal of Cranio-Maxillofacial Surgery</i> 41 (7): 603-609.			

Table 3. Studies with accuracy measurement of AM models [49].

5. Clinical applications

Three-dimensional printing has been available for over three decades. Despite that, medicine has benefitted from its application recently [23–25]. As mentioned before, 3D printed models can be useful in different aspects of maxillofacial surgery such as templates, splints, tailored implants, and others [23–27]. These models can reduce surgery duration and enhance the results [10]. RP technology can become very useful for both doctor and patients in treatment planning for each patient individually [56]. Medical applications of 3D printers have expanded after recent advancements of these systems. In oral and maxillofacial surgery, 3D printing methods have been utilized for different purposes including distraction osteogenesis and treatment of craniofacial deformities [57, 58]. The following are the main applications of 3D printing technology in oral and maxillofacial surgery:

5.1. Surgical planning

Since 3D printing can distinguish traumatic and pathologic defects more effectively, it has proven to enhance diagnosis and treatment in the maxillofacial region. This feature results in precise decision making. In the aspect of pathologic lesions, 3D printing is capable of presenting spatial relationships to surrounding components [52–54, 58–63]. These important visualizations can minimize operative complications [26].

By 3D printing, surgeons can visualize the procedure and forecast the challenges to gain better results before they even start. Three-dimensional printing can produce models rapidly with acceptable accuracy and structural details to allow for better outcomes and reduced operating durations [64].

5.2. Trauma surgery

3D printers can facilitate the treatment of trauma patients with recent or delayed fractures and defects. Different fractures of maxillofacial structures can benefit from 3D printing but orbital wall fractures are the best targets for these methods [65–67]. These patients can be treated by 3D customized reconstruction of orbital wall defects with titanium mesh or sheet [68]. Before the surgery begins, titanium mesh or plate is adapted precisely on the 3D printed replica to help shortening the duration of general anesthesia [69, 70].

Complicated and detailed anatomy of the orbit makes it difficult to reconstruct orbital defects. Postoperative enophthalmos or diplopia always happens without accurate and proper reconstruction of orbital walls. Surgeons can solve these complications by using 3D printed titanium mesh using the contralateral orbital anatomy [30, 71].

Sas̃a et al. evaluated the application of custom-made implants using 3D printing system to reconstruct in blowout fractures of the orbital floor. After the surgery, average orbital volume (OV) of the affected side noticeably decreased, and OV of corrected orbit was not different compared to the unaffected side [72].

Chandan Jadhav et al. treated three patients with medial orbital wall fractures using 3D models. They used the 3D model as a template to measure and harvest bone graft from iliac

crest easily and precisely, resulting in perfect adaptation and reduced operation time (**Figures 4 and 5**) [56].



Figure 4. The rapid prototype metal orbital floor reconstruction in the orbit of the stereolithic skull reconstructed from the original CT scans [71].

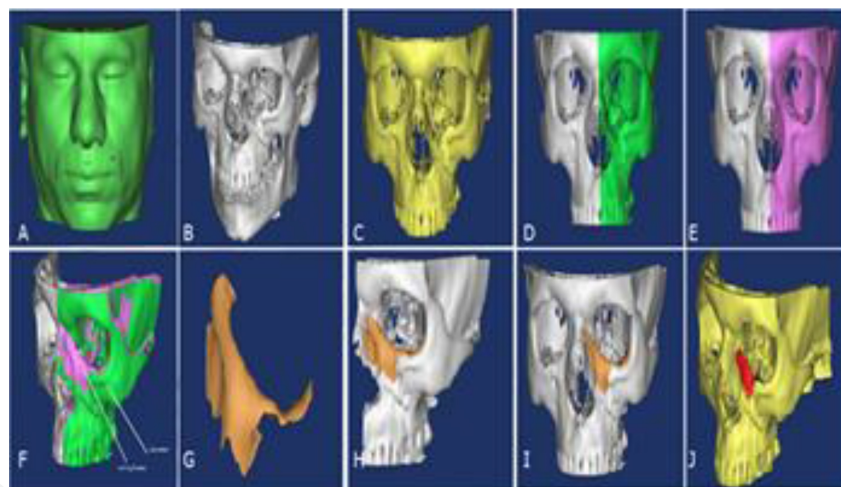


Figure 5. Treatment of orbital floor defect in a trauma patient using 3D printing technology. (a) 3D model designed based on CT scan images; (b) removal of soft tissue on differences between soft and hard tissue density; (c) removal of excess bone; (d) dividing the face into two halves from symmetry line; (e) mirroring the uninjured side on the other side; (f) comparison of the injured half and the mirrored half and finding their differences; (g) differentiation of the ideal design; (h) precise adaption on injured half; (i) correction of the design by removal of excess components; (j) final model.

5.3. Orthognathic surgery

Precise planning and decision making based on exact diagnosis is critical in the success of orthognathic surgeries [73]. As mentioned earlier, 3D printing technology shows some clinically noticeable inaccuracies for orthognathic surgery which is troublesome for ideal dental occlusion [30].

5.4. Facial prosthetics

There are reports of fabricating prosthetic nose [74, 75], ears [76, 77], eyes [78, 79], and face [80, 81], in the last 10 years. Literature indicates that better esthetic and functional outcomes are accomplished with the application of 3D printing in comparison to the traditional prosthetics (Figure 6) [76, 82].

Facial prosthetics fabricated with RP methods are being utilized successfully. Ancient Egyptians were the first people to apply facial prosthetics in 500 B.C [83].

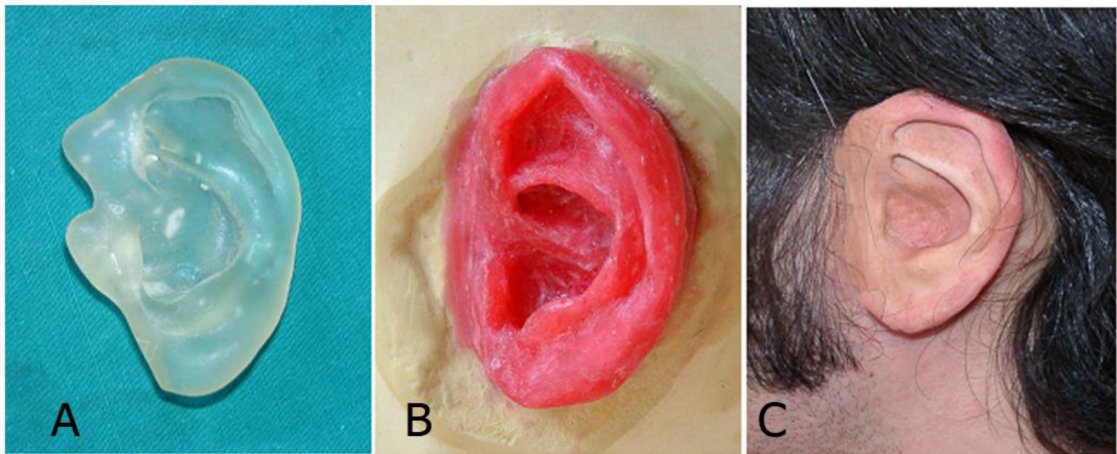


Figure 6. (a) 3D model obtained by stereolithography; (b) stereolithographic model turned into wax; (c) finished auricular prosthesis [85].



Figure 7. Application of 3D printing in lateral nasal osteotomy. (a) Planned osteotomy lines of lateral nasal osteotomy are drawn with a skin marker on the 3D model; (b) compensate the thickness of the soft tissue lining of the nose with thick wax; (c) trimming the custom-made splint on the 3D model; (d) performing the lateral nasal osteotomy in line with the surgical plan; (e) pre- and postoperative views [117].

Facial prosthetics have evolved extensively with the application of 3D printing technology. This technique allows producing replicas of facial structure within just hours [84].

Impression procedures are the common method to manufacture facial prosthetics. Longer duration of production, soft tissue distortion, and patient discomfort are the main limitations of this process. Lately, 3D printing has been utilized to produce facial prosthetics to reduce limitations of traditional procedures. Additive manufacturing technology can simplify the procedure, shorten laboratory procedures by excluding impression procedures, and model wax-ups. No doubt, 3D printing will become the modality of choice to manufacture facial prosthetics [85]. Additive manufacturing is mainly used for hard tissue reconstruction. However, it is useful in soft tissue contouring [5, 86] such as auricular reconstruction in patients using the contralateral ear (**Figure 7**) [87].

Auricular prosthesis production consists of multiple time-consuming processes demanding patient presence. These procedures are (1) impression making, (2) fabricating a wax replica, (3) manufacturing a mold, and (4) creating the prosthetic object with a suitable color. 3D printing technique simplifies and shrinks the first three steps. The process can be completed in 24–48 hours instead of a week [88].

5.5. Customized TMJ reconstruction

In the field of TMJ(Temporomandibular Joint) reconstruction, sufficient exposure and access is critical to prevent damaging many vital structures in this area. Alloplasts and allografts must be accurately placed to regain correct function of the jaw [89]. 3D printing can become useful in the treatment of TMD(Temporomandibular Joint Disorders) patients with total condylar resorption [18]. Mehra et al. treated a patient by bone grafting and TMJ prostheses using additive manufacturing. 3D printing aided in measuring exact proportions of the bone needs to be harvested [22].

5.6. Dental implants

Creation of new dental implants has benefitted from 3D printing technology [90, 91].

3D printing acts as a tool to create dental implants with complicated geometries [14].

Drilling guides are of great value to transfer implants from their planned positions. Manufacturing a drilling guide by conventional methods is time-consuming and requires multiple patient visits and extensive laboratory work. RP facilitates this with solely a single consultation prior to operation. In this session, data are gathered, and the guide is virtually built and later will be manufactured by the 3D device [92].

5.7. Complex facial reconstruction

Pathologic lesions, traumatic events, and infections are main etiologies of mandibular defects needing partial resection and bone reconstruction [93, 94]. Maintaining acceptable esthetic and functional outcomes and facial symmetry are the main goals of mandibular reconstructions. Titanium reconstruction plates are biocompatible and adaptable alloplasts for temporary

reconstructions [95]. For more reliable reconstruction, autogenous bone grafts are commonly used. Complex mandibular morphology and muscular attachments moving the jaw in unfavorable positions are challenging to oral and maxillofacial surgeons in mandibular reconstructions [23]. 3D printing technology can be used in different aspects of facial reconstruction. This technology is widely used for mandibular reconstruction [96]. Better anatomical understanding, proper plate adaptation, plate pre-bending, precise bone harvesting by utilizing negative templates of the defect, reduced bone-plate distance, decreased duration of surgery, less blood loss, and shortened duration of general anesthesia are the main advantages of using additive manufacturing in mandibular reconstruction (**Figure 8**) [23, 96].

Hanasono and Skorackil indicated that 3D printing can reduce surgery duration up to 1.4 hour [97].

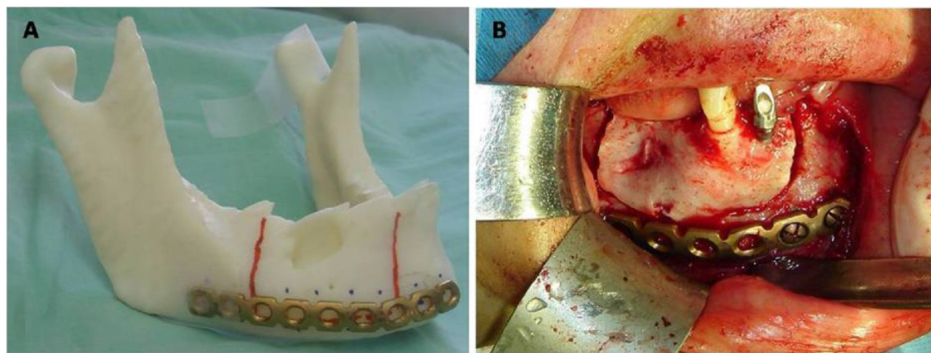


Figure 8. (a) Precontoured reconstruction plate before marginal mandibulectomy aiming to reinforce the remaining thin mandibular lower border; (b) note the anatomic alignment of the precontoured plate to the lower mandibular border [23].

6. Improvements in learning, training, and practice

6.1. Surgical education

Medical training can reform with enhancements of 3D printing technology [84].

As oral and maxillofacial surgeons, we are expected to master detailed morphology of the head and neck region and their spatial relationship. Patients and medical trainees and residents can benefit from 3D printed models [26, 98]. High maintenance charges, cultural and social complications, and formalin-related safety issues are making cadavers a limited source for medical education [99, 100].

Medical trainees can have better understanding of anatomical structure with 3D printed models.

These models allow a thorough and complete training before a surgery even begins [101, 102]. Operators can perform complicated surgeries on 3D models without any concerns and complications [103]. 3D printing also can aid in better understanding of patients' medical

situation rather than a flat 2D screen [12]. Kah Heng Alexander et al. conducted a double blind randomized controlled trial to compare the success of 3D printing with human cadavers for distinguishing external cardiac anatomy. 3D printed models had significantly higher scores in comparison to the cadavers or combined groups [98]. With the enhancement of new materials, 3D printed models will be more accurate in the future [104–106].

6.2. Patient education

Fulfilling patient expectations is critical to have successful surgical outcomes. Surgeon-patient professional relationship can be simplified using 3D printing. In preoperative consultations, patients can understand surgical details, different results, and potential obstacles. Therefore, 3D printed models can aid gaining informed consent. [103]. CT/MRI scans that we use today to explain the procedure for the patients are usually hard to understand for uneducated patients. Patients mostly do not comprehend the situation.

Literature has shown that 3D printed models result in better training of both patients and medical trainees [26, 107, 108]. Also having in-office preoperative and postoperative 3D printed models of specific surgeries can help patients justify their expectations [26].

Patients' families can also benefit from additive manufacturing since they might have positive impacts on patient satisfaction. These models could be utilized to form a library for future educational goals [109].

7. Prospective visions

Three-dimensional printers are a new and emerging technology with the ability to manufacture physical objects from digital files. Decreasing hardware costs have made this technology affordable for use in the office setting [26]. 3D printing technology enables more effective patient consultations, increases diagnostic quality, improves surgical planning, acts as an orientation aid during surgical procedures, and manufactures guiding template segmental resections. In the future, additive manufacturing might be capable of organ bio-printing [30]. Surgery is a practical art! The surgeon often uses direct physical intervention in the treatment of patients. Surgical procedures must be accurately planned for each patient individually to minimize complications and increase benefits. In oral and maxillofacial surgery, potential uses extend to surgical planning, education, and prosthetic device design and development. RP is not utilized in conventional clinical applications but can revolutionize oral and maxillofacial surgery in the future [26]. To clarify and understand what is the best prediction for the future of the technology itself, production time of objects and costs should also be considered. Different researchers have indicated that they have found 3D printing a cost-effective technology [110–112]. However, some other investigators have doubted efficiency and price of RP [113]. 3D printed replicas are considered to be more precise and cost-effective for patients and trainee education compared to other techniques [114]. This method also eliminates the need for animal studies [64]. 3D printing technology is here to improve our lifestyle and health care in the twenty-first century [103].

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