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3D-PRINTING: CONTEMPORARY PROSTHODONTIC TREATMENT

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ABSTRACT:

Digital dentistry has gained in popularity among clinicians and laboratory technicians because of its versatile applications. Three-dimensional (3D) printing has been applied in many areas of dentistry as it offers efficiency, affordability, accessibility, reproducibility, speed, and accuracy. 3D Printing is a technology that can produce complex shapes according to computer design using patient’s anatomical data. Its initial use was as pre-surgical visualization models and tooling molds,but now 3D Printing has slowly evolved to create devices such as implants, scaffolds for tissue engineering, diagnostic models etc. It is a form of additive manufacturing technology where a three-dimensional object is created by laying down successive layers of material. This paper will give an insight on how 3D printing works, its application in 3D printing of dental restorations and its future direction

KEY WORDS: 3D-printing, rapid prototyping, additive manufacturing of prosthetic constructions,stereolithography

INTRODUCTION

Three-dimensional (3D) printing is a rapidly developing technology that has gained extensive acceptance and application in dentistry (Kessler, Hickel and Reymus, 2020)[1] . It is also known as additive manufacturing (AM), rapid prototyping or layered manufacturing (Jain, Supriya and Gupta, 2016)[2]. The term 3D printing is generally used to describe a manufacturing approach that builds an object by laying down one layer at a time, adding multiple layers (Dawood et al., 2015)[3]. The main idea behind this innovation is that the 3D model is sliced into many thin layers and the manufacturing or assembling equipment uses geometric data to build each layer sequentially until the final desired product is completed. Scanners might be used to examine and record the anatomy that has to be delivered to the 3D model. The 3D model is cut after which, it is prepared to be taken into the 3D printer of the appropriate type. This is done possibly by the means of USB, Wi-Fi or SD. The record is transferred to a 3D printer and then the model or item is prepared to be 3D printed in layers. The 3D printer uses each 2D picture to make a three-dimensional object. Objects with geometry ranging from simple to complex can be made. This procedure is known as a slicing (Liu, Leu and Schmitt, 2006)[4]. It is more often and correctly described as additive manufacturing, and also as rapid prototyping (Andonović and Vrtanoski, 2010)[5]. 3D printing has been used since the 1980s. In 1983 Charles printed the first 3D object using the technique of stereolithography (Strub, Rekow and Witkowski, 2006)[6].

However, modern additive manufacturing technology was introduced approximately three decades ago (Stansbury and Idacavage, 2016)[7] and its application in dentistry is recent. Additive manufacturing (AM) which involves the deposition of material in increments, is an innovation over subtractive manufacturing (SM) where an object was cut off from a block of material (Azari and Nikzad, 2009; Abduo, Lyons and Bennamoun, 2014)[8] The term Additive Manufacturing (AM) is used by the ISO and the American Society for Testing and Material[10,11]. However, in medical and dental applications and general practice in other fields, the term 3D printing is more preferred (Anderson, Wealleans and Ray, 2018)[9]. 3D models are produced with the help of CAD/CAM or 3D scanners. 3D imaging plays an important role in the diagnosis and treatment planning of dental diseases.)

3D-printing is a type of additive technique which has progressed swiftly in various fields of dentistry as it has the potential to overcome known drawbacks of the subtractive techniques such as fit problems, wasting of considerable amount of raw material, excessive abrasion of milling tools, microscopic cracks into the ceramic, limitations of the precision fit of the inside contour which depends on the smallest tool .The aim of the present paper is to make a review of the applications of 3D-printing technologies in contemporary prosthodontic treatment.

MATERIALS & METHODS:

The 3D printing industry has recently exploded due to the reduced manufacturing costs of 3D printers and to their improved printing precision and speed, allowing for huge advances in medical equipment, implant material, and cell printing. The preparation of organ models, rapid manufacturing of personalized scaffolds, and direct printing at the defect site can be achieved by 3D printing technology based on a patient’s imaging data such as CT or magnetic resonance imaging. In this way, 3D printing technology brings new possibilities for building bionic tissue or organs and solving the donor-shortage problem.

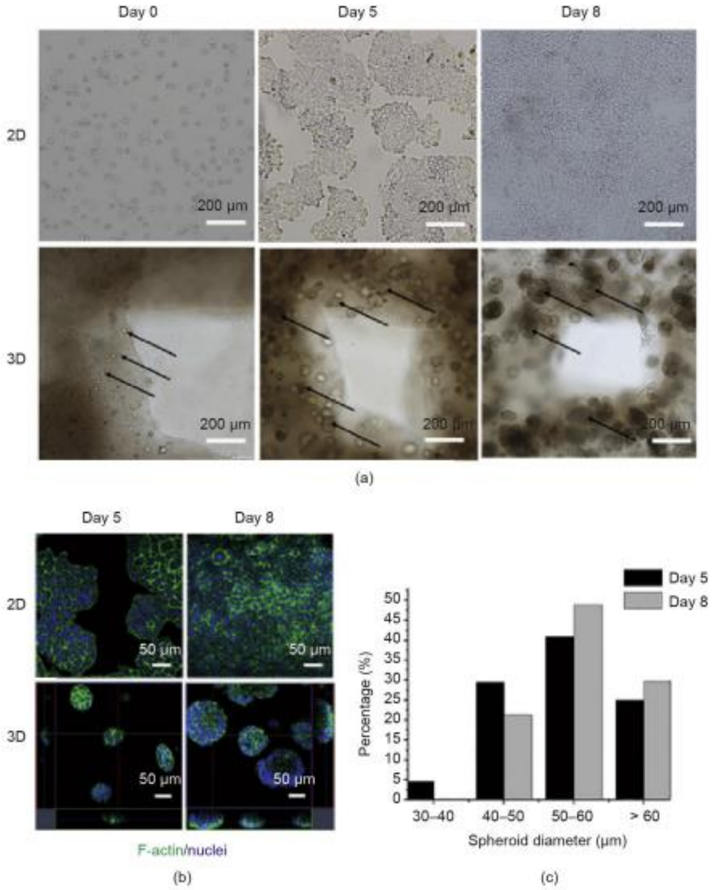
Current research on 3D printing technology for medical applications can be classified into the following four main areas of focus: ① research on manufacturing pathological organ models to aid preoperative planning and surgical treatment analysis[12] ; ② research on personalized manufacturing of permanent nonbioactive implants; ③ research on fabricating local bioactive and biodegradable scaffolds; and ④ research on directly printing tissues and organs with complete life functions[13-15]. Although such applications remain far from widespread clinical use due to several key technical and basic scientific issues that are yet to be overcome, notable scientific advancements and applications have been achieved in these areas.

Four levels of 3D printing for medical applications

1. Organ models to aid preoperative planning and surgical treatment analysis :

High-fidelity physical organ models play a significant role in clinical treatment and in medical education. Conventional manufacturing processes, such as casting or forging, waste so much time in preparing expensive tooling, and always ignore individual differences among patients [16]. 3D printing has the advantage of rapidly fabricating customized medical models at a lower cost, since there are no tools involved. 3D printed organ models primarily help doctors to perform surgical analysis and preoperative training.

A group of researchers from China and America have used 3D printing technology with HeLa cells and gelatin/alginate/fibrinogen hydrogels to successfully construct in vitro cervical tumor models [17], thus providing vivid 3D imaging of the tumor environment. As shown in Fig. 1[17], HeLa cells form round spheroids with smooth surfaces and tight cell–cell connections within the 3D hydrogel, while exhibiting a flat and elongated morphology on 2D tissue culture plates.



(a) (b) (c)

Fig. 1. Cellular morphological changes in a 3D construct and 2D planar culture. (a) HeLa cells for different periods; (b) distribution of the cytoskeleton after staining; (c) distribution of spheroid diameter in 3D HeLa/hydrogel constructs [8].

Researchers at Monash University, Australia, developed a unique 3D printed human anatomical model made from gypsumlike powder or plastic by scanning real anatomical specimens using CT or a planar laser scanner. This series of high-resolution 3D printed anatomical replicas, including limbs, chest, abdomen, head and neck, and other major body parts (Fig. 2), is available for anthroponomy training in medical colleges or hospitals.


(a) (b)

Fig. 2. 3D printed human anatomical model kits, including (a) head and (b) arm, published by Monash University.

Cardiologists from Spectrum Health Helen DeVos Children’s Hospital in Grand Rapids, Michigan announced that they have 3D printed a more detailed patient cardiac module (Fig. 3) using synthetic data from multiple imaging technologies, which sets the precedent for utilizing both CT scans and 3D echocardiography data to print a 3D mixed model.

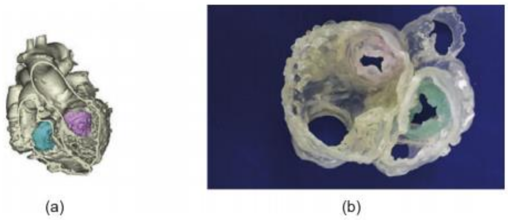

(a) (b)

Fig. 3. (a) CT scan and 3D echocardiography data model; (b) 3D printed cardiac module combining various medical imaging technologies.

2.Permanent non-bioactive implants :

Permanent medical implants commonly used in dentistry and orthopedics require non-degradable biomaterial and offer good biocompatibility after surgical operation.

Fig. 4 shows postoperative imaging of a custom prosthetic reconstruction. In that study, most patients recovered excellent motor function with few complications.


(a) (b)

Fig. 4. Postoperative (a) anteroposterior and (b) lateral radiographs of custom prosthetic reconstruction [13].

Current technology for the 3D printing of permanent implants is relatively mature; thus, the present study focuses on three aspects: First, the development of medical materials with better performance is discussed. For example, Winder et al. [20] fabricated custom cranial titanium (Ti) implants made directly from stereolithographic resin (Fig. 5(a)), thus greatly simplifying the process. Second, we present the uses of advanced technology to manufacture implants with excellent mechanical properties matching those of bone. For example, SLM Solutions in Germany fabricated a Ti hip implant (Fig. 5(b)) for an Australian patient using a selective laser melting (SLM) process. This high-strength and lightweight implant had good compatibility with human tissue. Third, improving the biocompatibility and preventing infections of existing mature medical materials by surface modifications in order to meet medical requirements are overviewed. As shown in Fig. 6(a), Bian et al. [21] from Xi’an Jiaotong University associated hydroxyapatite (HA)-coated porous Ti, which is regarded as the carrier, with bone morphogenetic protein-2 (BMP-2) via gelatin. They successfully prepared 3D porous Ti with osteoconductivity composed of an osteoinductive composite material. Compared with the tissue slices in the control group (Fig. 6(b)), Fig. 6(c) and Fig. 6(d) show that more bone mass newly formed in the BMP-2 gelatin/HA porous Ti group after 6 weeks, and that the surfaces of new bone are in direct contact

3. Fabricating local bioactive and biodegradable scaffolds :

Fig. 5. (a) Stereolithographic resin model of a full skull with a custom Ti plate in place; (b) hip implant fabricated by SLM Solutions in Germany [14].

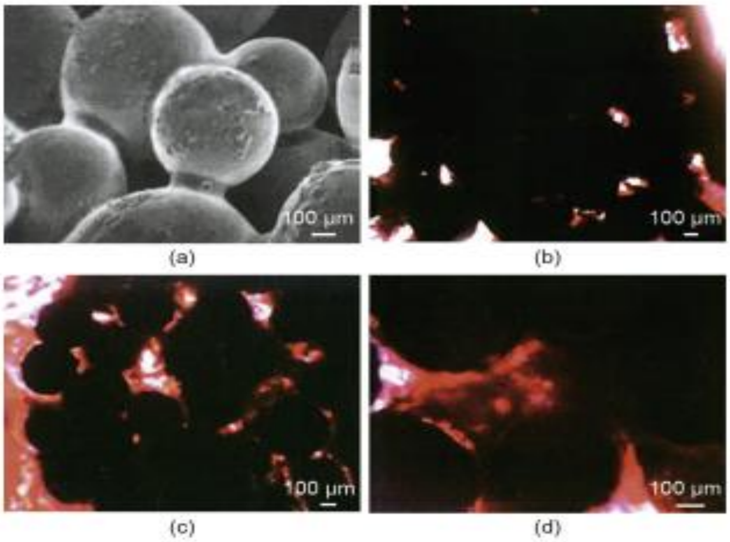


Fig. 6. (a) X-ray film of BMP-2 gelatin/HA porous Ti complex; (b) tissue slices observed at 6 weeks after implanting HA-coated porous Ti; (c) tissue slices observed at six weeks after implanting BMP-2 gelatin/HA porous Ti complex; and (d) tissue slices observed at 24 weeks after implanting BMP-2 gelatin/HA porous Ti complex [15].

There are two possible routes for manufacturing tissues and organs, depending on whether cells are directly manipulated during the formation process. The first route is tissue engineering (Fig. 7(a)), also known as indirect cell assembly, which involves first forming a 3D scaffold, and then seeding cells[22] . The second route, known as direct cell assembly, formulates both cells and materials into a composite

structure . As shown in Fig. 7(b) and Fig. 7(c), the mixture of cells and gel is encapsulated into 3D scaffolds that are composed of another kind of gel with good mechanical strength, or are printed directly in order to control the spatial distribution of cells and even realize in situ repair

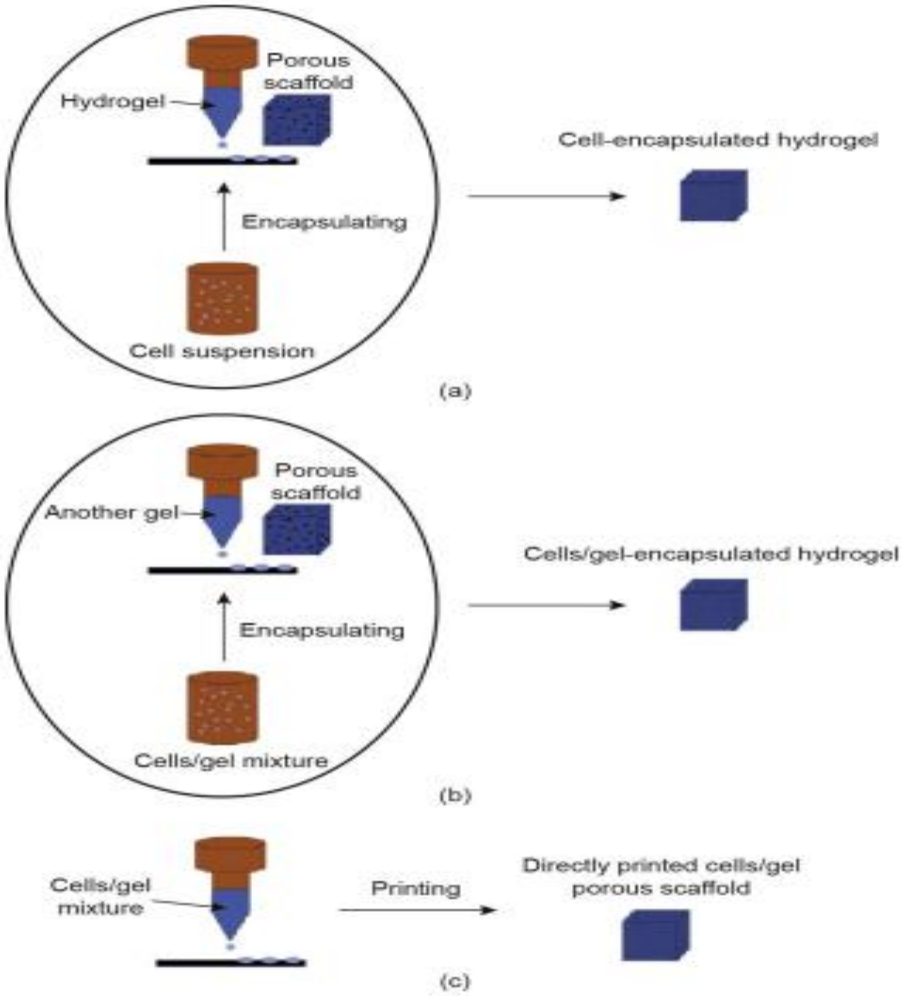


Fig. 7. Schematic views of three processing methods for personalized biodegradable scaffolds. (a) encapsulating cells directly into gel scaffolds; (b) encapsulating cells/gel mixture into 3D scaffolds; and (c) directly printing cells/gel.

4. Directly printing tissue and organs :

Encapsulating cells into biodegradable scaffolds via traditional tissue engineering cannot ensure that cells are precisely implanted into inner scaffolds, and growth factors will only affect the growth and differentiation of surface cells. In 2000, Professor Thomas Boland of Clemson University, USA, proposed a new concept called ‘‘cell and organ printing” that represents the origin of modern 3D bioprinting technology. In 2009, Ganovo company in the United States was the first one to use 3D printing technology to produce vascular prostheses[23]. The Southern California University of Health Sciences and the University of Michigan mixed agarose as a support with cells to co-print a vascular network less than 3 mm in size using a 3D printing device [24]. Scientists from the Wyss Institute for Biologically Inspired Engineering, Harvard University [25], reported a new 3D bioprinting method for fabricating complex living structures with integrated microvessels using multiple print heads and special ‘‘ink”. Mannoor et al. [26] generated a bionic ear by 3D printing a chondrocyte-seeded alginate hydrogel matrix and infused silver nanoparticles in the anatomic geometry of a human ear and cochlea-shaped electrodes (Fig. 8(a,b)). The printed bionic ear possessed better auditory sensing of radio frequencies than the human ear. A biologist from Cornell University utilized stem cells and biopolymer materials to print a functioning cardiac valve (Fig. 8(c)), and the stem cells gradually differentiated into human cells. There currently exist some 3D printed organs for clinical applications. As shown in Fig. 8(d), researchers at the University of Michigan implanted a 3D printed artificial trachea into the windpipe of an infant with a birth defect to assist breathing, representing the world’s first successful 3D printed human organ transplant.

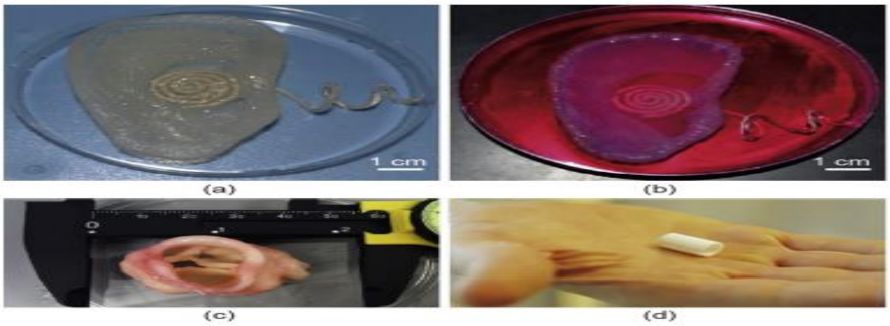


Fig 8.(a) Image of the 3D printed bionic ear immediately after printing; (b) image of the 3D printed bionic ear during in vitro culture; (c) the 3D printed cardiac valve; (d) the 3D printed artificial trachea

ADDITIVE MANUFACTURING : Engineering has invented various technologies for additive manufacturing. **Stereo lithography, fused deposition modeling, selective electron beam melting, laser powder forming and inkjet printing** are the most used methods in dentistry[32].For the purpose of layer-by-layer structuring of the real dental restoration, first, the digital image of the object is sliced in the CAD unit by special software. Then the manufacturing of the 3D prosthesis continues with a process almost similar to printing on paper – one layer on top of another. It is the so-called **“3D-printing”**(27-33)(Fig. 9). Synonymous terms that are often used in different science sources are also: **“layered manufacturing”, “freeform fabrication”, “rapid prototyping”, “rapid manufacturing”** (31,33,34,35,36).3D printers are machines that produce physical 3D models from digital data by printing layer by layer. They can make physical models of objects either designed with a CAD program or scanned with a 3D scanner. Stereo lithography (SLA) is the first additive technology that was created by Charles Hull in 1980 for manufacturing of prototypes, models and casting patterns [37] .The indications for the use of SLA gave the name of the term “rapid prototyping”.

Fig 9: The process of 3D-printing

Additive manufacturing technology has a range of applications such as **stereo lithography, laser forming, selective electron beam melting** and **inkjet printing**.

Stereo lithography works on the principle of making solid objects by successively printing thin layers of UV curable photopolymer on top of the each layer as shown in fig 10. The ultra violet light draws the object and therefore cures it with the input as digital CAD. SLA can be used for studying pre operatively human models from CT (DICOM) data, for preparation of customised surgical implant guides and also as resin models for lost wax casting.

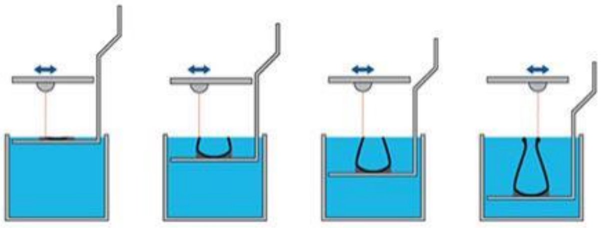


Figure 10 Stereolithography process

Stereolithography : It is the earliest and most commonly employed technique (Kim et al., 2016)[46].First 3D model was created using this apparatus by Charles Hull .SLA could be used to produce implant surgical guides, surgical and burn stents, obturators, etc (Jain, Supriya and Gupta, 2016)[47]. The main disadvantage of SLA is the unavailability of biocompatible resin with properties suitable for SLA .Another disadvantage is that the process of SLA is costly when it is employed for large objects (Dawood et al., 2015)[39].

DISCUSSION :

It was developed at Massachussets Institute of Technology. It is a type of additive manufacturing in which materials are joined to make objects from 3D model data, usually layer upon layer. Once the CAD design is finalized, it is segmented into multislice images. For each millimetre of material, there are 5–20 layers, which the machine lays down as successive layers of liquid or powder material that are fused to create the final shape. Some of the properties that distinguish 3-D printing from subtractive manufacturing are

1. incremental vertical object build-up
2. no material wastage
3. large objects produced
4. passive production (i.e., no force application)
5. fine details production.

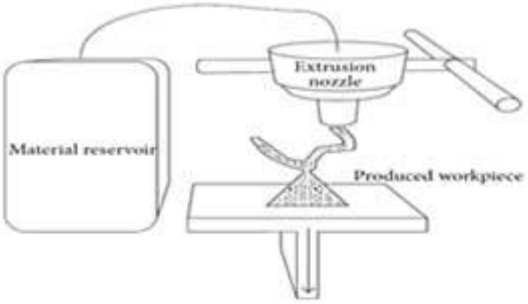


Fig.11: 3-D printing procedure

Fig.12:-Dental 3-D printer

APPLICATIONS IN PROSTHODONTICS

Custom trays can be manufactured or 3D printed from computerised scans of impressions or models . Model printing directly from intraoral scan helps quick fabrication of prosthesis. In RPD, resin framework can be tried in a patient's mouth before casting. In fixed and removable prosthodontics, restorations could be designed using CAD software and crowns, bridges, copings, abutments, etc can be printed using 3D printers .Printing of coping or full contour resin patterns can avoid the process of making manual wax patterns, followed by which, the consequences of wax distortion can also be minimized. Provisional crown and bridge resins were 3D printed and showed higher accuracy and good mechanical properties and marginal fit when compared to conventional ones .

The use of 3D printing technology has gained popularity and acceptance in dental implantology due to the introduction of guidelines for a surgical procedure which implies the usage of surgical guides.for insertion of dental implants. 3D printers also print bone tissue favouring the requirements of the patient that can act as a biomimetic scaffold in the mouth for bone cell enhancement, tissue growth and differentiation . 3D printed bone implants can replace the deficient part using biocompatible materials like PEEK (polyetheretherketone). 3D printing is capable of producing implants with bone-like morphology, in order to reduce the stress-induced on the bone .Prefabricated dental implant surgical guides can be used for verifying or guiding the proper location, angulation and rotational positioning of the implant prior to the placement in order to provide better aesthetics and functionally stable prosthesis.

Presently, 3-D printing is being used in dental laboratories around the world.maxillofacial prostheses can be fabricated with high precision and excellent colour matching.the CAD data can be stored in computer and retrieved anytime for future use.So a virtual library can be created and if any patient wants to replace prosthesis,they can be fabricated in less time.

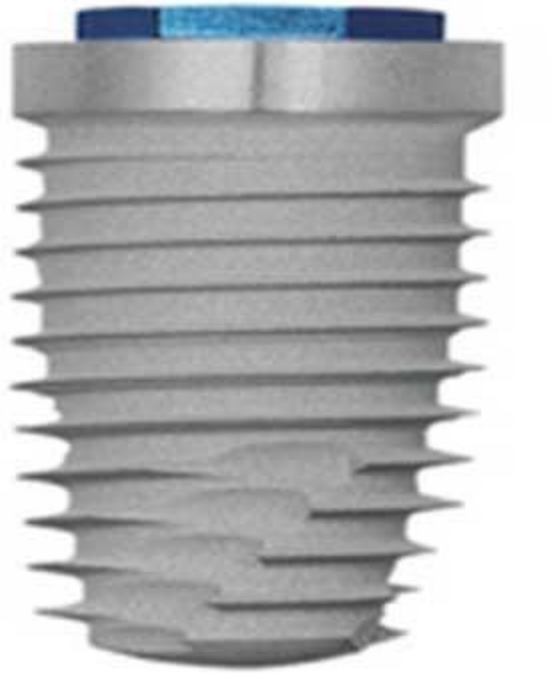


Fig.13: 3 D printed maxillofacial prosthesis Fig.14: 3-D printed porous implant

Porous implants fabricated using 3-d printing helps in bone growth and attachment.

Complex wax patterns involving undercuts can also be fabricated using this technique.

3-D printing has enabled us to fabricate precise fitting cast partial denture frameworks.Surgical templates and occlusal splints.

Fig.15 :3-D printed wax patterns

Fig.16: 3-D printed implant surgical guide

Fig.17: 3-D printed Dental model

Anatomical models can be fabricated for patient education easily

Fabrication of Wax Patterns for Prosthetic Constructions

Fig 18- wax patterns produced by 3D printing-(a) and 4-part bridges produced by SLM of co-cr alloy (b) (1-as received SLM bridges,2- after mechanical treatment,3- after sand blasting)

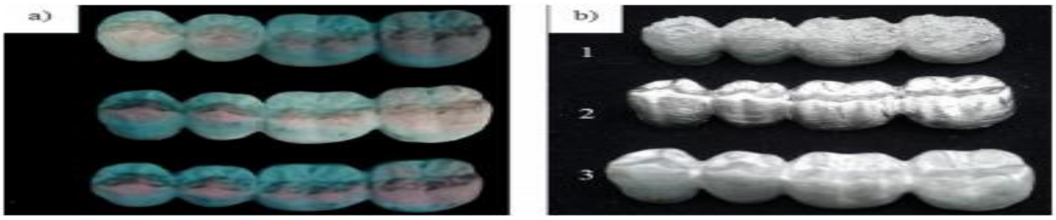


Fig 19- Polymer temporary bridges,produced by stereolythography

Direct Fabrication of Prosthetic Constructions from Metal Direct fabrication of metal prosthesis is already possible through selective laser sintering/selective laser melting technologies (SLS/SLM) (Fig.18). The new technologies skip the long preparation process in conventional lost-wax manufacturing and respectively eliminate the risk of failure especially in cases with metal parts with complex shape as are the prosthetic constructions.

3D Printing of Molds for Metal Casting Ceramic casting molds are fabricated trough an incremental printing method [38] without the need of manufacturing wax pattern and all of the following steps in the wax-eliminating process [39,40].

3D Printing of Molds for Facial Prosthesis Rapid prototyping aided manufacturing of facial prosthesis molds is alternative to the conventional flasking and investment procedures. This modern trend in the fabrication of facial prosthesis shortens the whole process and allows multiple pourings from a single mold [41]

3D Printing of Molds for Complete Dentures Advanced manufacturing technologies are used in the field of complete dentures mainly to fabricate a physical mold of the denture through a CAD processSince the mold is ready the complete denture undergoes the traditional manufacturing process to be ready for the dental office(39,40,42).

Fig.20 :-3-D printed complete denture

Fabrication of All-Ceramic Restorations The direct inkjet advanced technology can be implemented for fabrication of green-zirconia allceramic restorations. The 3D printing of allceramic restorations is still an object of science researches and experiments.

3-D BIOPRINTING

Printing and patterning in 3 dimensions of all the components that make up a tissue(cells and matrix materials) to generate tissue analog structures has been termed bioprinting.Bioprinting allows us to replace missing parts with living tissues.Porous bone scaffolds can be printed by Fused Deposition Modeling(FDM) and used as graft for ridge preservation. When these scaffolds were combined with recombinant human BMP [7] (rhBMP-[7]) and implanted in 10-cm critical-sized defects in a sheep model, defect bridging was observed within 3 mo, and after 12 mo, significantly greater bone formation and superior mechanical strength were observed for the 3D printed scaffolds relative to the gold-standard bone autologous graft (Reichert et al.2012).[43]

Three dimensional printing was also used to engineer scaffolds and regenerate the multi tissue interface arrangement of bone and cartilage in the TMJ (Schek et al. 2005).[44] 3D printing applied to cartilage repair have included the fabrication of a chondrocyte-seeded alginate hydrogel matrix with an ear shape and a conductive electronic component capable of transmitting sound (Mannoor et al. 2013)[45]. Thus 3-D printing of cartilages of TMJ can alleviate pain and provide better quality of life for patients.

LIMITATIONS: 3D printing is a costly technology. The techniques involved in 3D printing have disadvantages of skin irritation, mess, inflammation due to contact and inhalation of powders, the requirement of support materials, etc. With furthermore research and employment of improved techniques in the upcoming years, the disadvantages of 3D printing could be corrected.

CONCLUSION: There is no doubt that in the future additive technologies will replace many stages and even the whole process of the conventional manual making of dentures and the specialists will need to control and participate in the CAD/CAM process only in the visualization part. The main advantages of the RP manufacturing of dental restorations are the significant decrease of the time needed for production cycle and the cost of the final restoration & very little manpower is needed.It also favors a collaboration between the dental laboratory and the dental office. Last but not least, there is the important fact that advanced technologies eliminate the risk of dimensional changes of the impressions and casts because they skip these procedures – the prosthetic field can just be scanned and the model directly printed without any disruption of the tissues. The dental laboratory does not need more square meters now because everything is stored simply in the computer hard disk. It also provides superior products with better color matching. Bioprinting reduces the need for artificial materials and uses more of living tissues and thus are better tolerated by body. This technology is still evolving and it contributes to brighten the future and widening the horizons of prosthodontics.

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