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Review Article

Studying the Use of 3D Printers in the Dental Prostheses Manufacture

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ABSTRACT

3D printing is a layered structure method that is utilized to make 3D models of intricate structures. 3D printing has many equipment, materials, and methods. The purpose of this review is to investigate the utilization of 3D printers in dental prostheses manufacture; in which we evaluated the types of processing materials, methods, and accuracy. A standard search technique was utilized in Google Scholar and PubMed databases. The inclusion criteria for the study were articles in English, in the prosthetics manufacturing field, and the use of the incremental method in the work stages, in the range of 2015 to 2024. Until now, in dental prostheses, the methods of Selective Laser Melting (SLM), Stereolithography (SLA), Material jetting (inkjet), and Fused Deposition Modeling (FDM) have been utilized to make surgical guides, implants, frames Metal, casts, removable prostheses, specialized tri, fixed prostheses, and cast patterns have been used. The appearance of digital and 3D technology has had a significant effect on prosthetic work and tooth reconstruction. The quality of prosthetic parts made using this method is clinically acceptable in most cases and can replace conventional techniques. Printing materials and methods utilized in dentistry are developing every day. For the successful utilization of this method, we require an up-to-date and complete knowledge of the material application method, limitations, and advantages of this new technique.

Keywords: Prostheses, Dental, 3D printers, New technique

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Introduction

Digital technology has created a huge transformation in all aspects of our lives, including dentistry; this is because computers work faster and more accurately and at a lower cost than humans do. Nowadays, all clinical aspects, such as patient record storage and collection, patient admission, treatment planning, patient diagnostic information processing and acquisition, getting data to form three-dimensional images, and restoration design and production in dentistry are performed with the assistance of computers. CAD-CAM (Computer-aided design-computer-aided manufacturing) dental prostheses have become universal in recent years. CAD-CAM-based technology usually includes 3 stages: 1- data digitization or collection, 2- CAD (data processing), and 3- CAM (production) [1].

There are two ways for 3D manufacturing (CAM): AM (Additive Manufacturing) and SUM (Subtractive Manufacturing). The reduction method is according to milling the material block with a lathe. This method reduces the treatment length and has many benefits for laboratory technicians, patients, and dentists. However, it has disadvantages including, limitations in the prosthesis thickness, wasting a lot of material, low validity in recording details based on the milling cutter size, and the high value of the equipment [2-7]. The incremental method, known as 3D printing and rapid prototyping, is according to increasing material layers. AM has excellent flexibility in design and, in inverse

the method of reduction, it has great accuracy in recording details and the material wastage amount is negligible. AM techniques have been introduced for complex structure construction and in recent years have entered different fields, including dentistry [8, 9].
3D printing is a layered structure method that is utilized to make 3D models of intricate structures. This method was first introduced in the 1980s by Charles Hull under the stereolithography name [10]. 3D printing in different fields of dentistry, such as surgical guides, dental models, implants, various dental veneers, etc. is becoming popular. The additive process is an alternative to the method of subtractive in which materials are mostly powder or liquid-based to build a solid 3D model [11]. The methods of AM have been developed for the fabrication of intricate structures. Large structure production, rapid prototyping, manufacturing defects reduction, and enhancement of mechanical properties are important factors in the improvement of AM technologies [8].
This research aims to present a comprehensive review of the 3D printing application in dental prostheses manufacture. The techniques were examined in terms of the main methods used, materials utilized, limitations, disadvantages, advantages, and utilization of each of them in manufacturing dental prostheses.

Materials and Methods

To find articles related to the topic, we used a search strategy and defined entry and exit criteria for it. PubMed and Google Scholar databases were searched using the words "Digital dentistry", "3D printing", "Dental Prosthetics", "Dental prostheses", "Rapid prototyping", and "Additive manufacturing". The search strategy for this review included three steps; first, the titles were reviewed, then the abstracts of the articles were read, and finally, the articles were selected and the full text was analyzed. The inclusion criteria were articles published in English between 2015 and 2024 about 3D printing in dentistry and included clinical, laboratory, and narrative review studies. Articles that did not address the topic, duplicate articles, and texts that were not in English were excluded from the study.

Results and Discussion

3D printing process

The ASTM (American Society of Testing and Materials) has defined AM as the process of materials joining layers to produce objects from three-dimensional information [12]. In general, the AM process consists of four steps. Creating a model of digital 3D by software using information from intraoral scanners or CT (computed tomography), data processing and cutting the 3D model into several 2D layers, 3D printing of the final product in layers, and final processing [13].
The AM process begins with creating a virtual 3D model from CBCT, MRI, or intraoral or extraoral scanner images by CAD software. CAD data format is converted to Standard Triangulation Language (STL) [14]. The dimensional exactitude of the final product depends on the thickness of each layer, which varies from a few microns to one millimeter. In addition, the materials used the type of printer and the complexity of the structure are effective on the final accuracy [15].

Different printing methods

According to the ASTM (American Society for Testing and Materials), additive manufacturing technology is classified into seven processes [12, 16]: 1) Vat photopolymerization, 2) FDM (Fused Deposition Modeling) or material extrusion, 3) PBF (Powder bed fusion), 4) Three-dimensional printing (3DP) or binder jetting, 5) Material injection or inkjet printing (Inkjet printing or Material jetting), 6) DED (Direct Energy Deposition), and 7) LOM (Laminated object manufacturing).

SLA (Vat photopolymerization stereolithography)

This method is one of the first methods of AM that was introduced in 1986 [17]. This technique is based on polymerization with light and an electron beam or UV light is used to start the chain reaction of monomer and resin **(Figure 1)**.

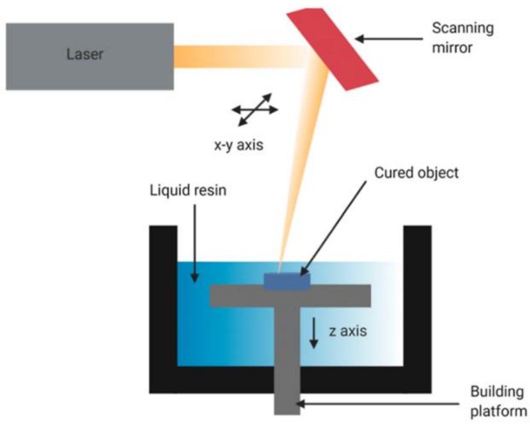


Figure 1. Schematic form of stereolithography.

Raw materials are liquid and contain photopolymers including polyamides, ceramic + resin slurry, composite resins, pure polymer resins, and elastomers [16]. The manufacturing platform is located in a liquid photopolymer tank. By changing the manufacturing platform and laser radiation, polymerization is performed and the first layer is created. To create the next layers, the manufacturing platform moves down and drowns into the tank so that the surface of the layer is covered by liquid polymer and then polymerization is done again with the platform movement. This process continues when all the layers are created and the 3D model is made. Final processing by heat (heating) or light (photocuring) may be required to increase strength [8].

Printing by SLA has high resolution and quality, but this technique is expensive and time-consuming, and the materials that can be utilized in it are very limited. Indeed, the resin is allergenic and causes inflammation because of the contact with the skin and eyes [18]. The light source energy and the exposure amount are the main factors that control each layer's thickness [17].

FDM (Fused Deposition: Modeling) or material extrusion

In this technique, a filament containing thermoplastic polymer is utilized for 3D printing. The filament is heated when the material is semi-liquid and the model desired is created layer by layer **(Figure 2)**. ABS (Acrylonitrile butadiene styrene), PLA (polylactic acid), and polycarbonate are the most commonly utilized materials.

The main feature of this technique is the thermoplastic character of the polymer, which causes the layers to be connected after printing, and during the printing process, it turns into a solid state at a temperature of room. The material melting point should be low, and since melting, its viscosity should be sufficient to be smooth and come out of the nozzle quickly, indeed, it should be strong and adequate to help the next layers [19].

Layer thickness, porosity, filament orientation, and diameter are the main factors that affect the mechanical attributes of the printed material. Easy process, high speed, and low cost are the main benefits of FDM. The low variety of thermoplastic materials, Low surface quality, Low mechanical strength, and layered appearance are the limitations of this method. The development of fiber-reinforced composites has enhanced the mechanical strength of the model of FDM printed [20]. Although the fiber orientation, the bond between the matrix and the fiber, and the porosity presence, are the main problems in using these composites [18, 20], they are used in prosthetics to make special trays.

PBF (Powder bed fusion)

In this technique, a powder-thin layer is spread on a plate and packed. In each layer, the powders are connected by a binder or laser. These plates are layered on each other top to make the final 3D product. Next, the powder additions are deleted by vacuum and if necessary, the final processing of the details is performed by sintering, coating, and infiltration **(Figure 2)**. The distribution and powder particle size, which determine the printed area density, is the main effective factor in this technique. In powders with a low melting temperature, a laser is utilized to connect the layers. A liquid binder is used in powders with high melting temperatures [21]. The main limitations of the powder bed fusion technique are the time-consuming and slow process, high cost, and high porosity when utilizing the binder [18, 21].

Binder jetting or three-dimensional printing

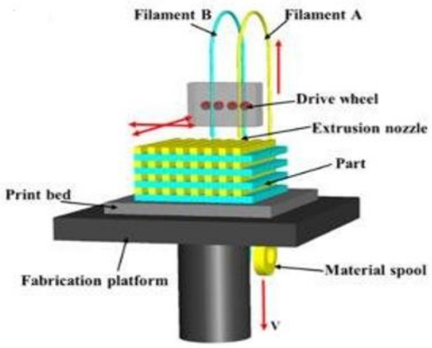
This system is similar to the PBF (powder bed) system, except that a liquid binder is utilized to bond the layers together. First, a powder layer is entrusted on the substrate and afterward, it is aligned with the roller. Next, Based on the information provided by CAD, the binder drops are expanse on the powder bed **(Figure 2)**. The chemical attributes of the binder, the size and shape of the powder particles, and the reaction between the powder and the binder play a vital role in the process of 3DP [16]. The porosity amount in this technique is higher than using a laser [18].

Inkjet printing or material jetting

It is a system of photopolymer injection that creates a completely 3D object layer by layer with several nozzles. The material chemical basis is like vat photopolymerization and is cured by ultraviolet light. This technique is utilized to make ceramics with an intricate structure in tissue engineering. In this technique, a ceramic stable suspension, such as zirconium oxide powder in water, is pumped with a nozzle onto a substrate and entrusted. The droplets form a continuous pattern that obtains adequate strength to support subsequent layers [22].

DED (Direct energy deposition)

They are utilized to create alloys. Raw materials are melted and afterward entrusted and bonded together. The difference between this technique and SLM is that powder is not utilized in this technique and higher energy is required to melt raw materials. Compared to SLM, DED provides lower surface quality and lower accuracy and can create less intricate models. This method is faster and cheaper [23].



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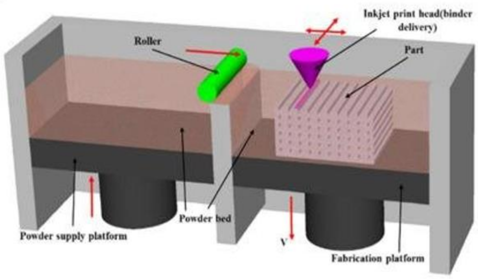

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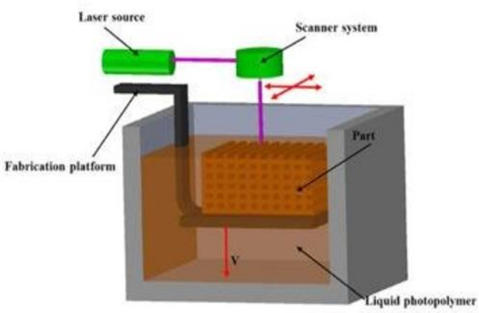

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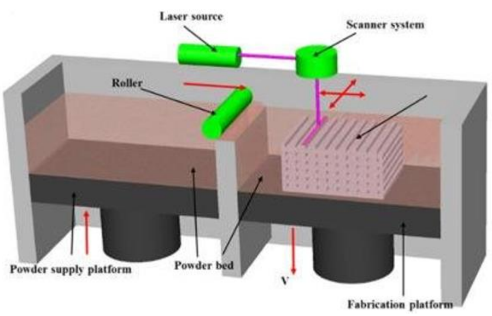

d)

Figure 2. Schematic figure of the four main AM techniques. a) fused deposition modeling, b) binder jetting, c) stereolithography, d) powder bed fusion [18].

LOM (Laminated object manufacturing)

In this technique, the materials are in the sheets form that are cut layer by layer using laser or mechanical technique and then connected **(Figure 3)**. Composite, ceramic, and metals can be utilized in this method. Depending on the material type, it needs final processing. LOM without processing has a lower surface quality and its dimensional exactitude is lower compared to powder bed technique [24].

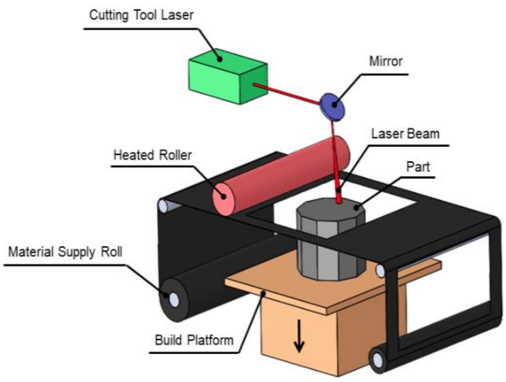

Figure 3. Laminated object manufacturing (LOM) schematic image.

3D printing methods comparison

Among the different methods, FDM is one of the popular 3D printing technologies because of its high speed, simplicity, and low processing cost. Originally utilized for 3D printing polymer filaments, however has been compatible with many other materials. Mechanical specification and quality of parts printed using FDM are lower compared to methods of powder bed such as SLM and SLS. In methods of the powder bed, adjacent powders are connected or bonded and melted by auxiliary adhesives, which results in more stringent separation, however incurs more costs and is a slower process. In the method of DED, an energy source (electron or laser beam) is utilized to melt metal powders, but compared to the method of SLM, a powder bed is not utilized, the raw materials are melted in layers before deposition, such as FDM, and a much higher amount of energy is utilized and is required to melt metals. Inkjet printing is relatively fast and is utilized for ceramics 3D printing, but it needs heat treatment after processing.

When using the right printing system, one should consider the materials availability, the medical attributes of the materials, the time needed, and the printed item's desired resolution. A problem that needs further study is the available material portfolio limitation, especially when changing beyond conventional polymers, as well as improving the printing speed and post-processing. Despite the AM method advantages, some drawbacks need further study and development to utilize this technology in different industries.

Materials used in 3D printing

Three categories of materials including polymers, ceramics, and metals are utilized in 3D printing.

Metals and alloys

The techniques utilized to print these materials are PBF and DED. Metals such as titanium, aluminum alloys, stainless steel, and its alloys, and nickel-based alloys are created by these methods [25].

Composites and polymers

Because of their high diversity, they are the main materials utilized in 3D printing. Polymers are utilized in the form of resin, monomer, powder, and thermoplastic filament. FDM is the main method utilized to fabricate composites [18, 19]. The polymer's low strength is the most essential problem in their use. To enhance the polymer's strength, elements are added to it, and composites strengthened with fiber, particles, and nanomaterials have been made so far [18].

Ceramics

The most common techniques for 3D printing of ceramics are Inkjet, PBF, and SLA. SLS can also be utilized, but the cracking possibility is very high [26].

3D printer application in dental prostheses

Printers are utilized in different fields of dentistry, such as prosthetics, maxillofacial surgery, implants, and tissue engineering. One of the first CAD-CAM uses was the make surgical guides and accurate anatomical models to assist in the simulation of surgeons the surgical process before surgery **(Figures 4 and 5)**. Brix and Lambrecht made the first models of anatomical with a lathe [27]. Lathes were limited to creating complex models. Klein *et al*. provided a method based on stereolithography [28].

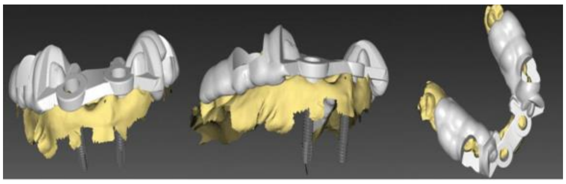

Figure 4. The surgical guide is designed virtually by correlation with the patient's CT data [29].

Implants can be created by the method of SLM using titanium powder, which is biocompatible. In addition, absorbable implants are made of phosphate and calcium. Some studies utilized hydroxyapatite and tricalcium phosphate to create implants and stated acceptable results [30].

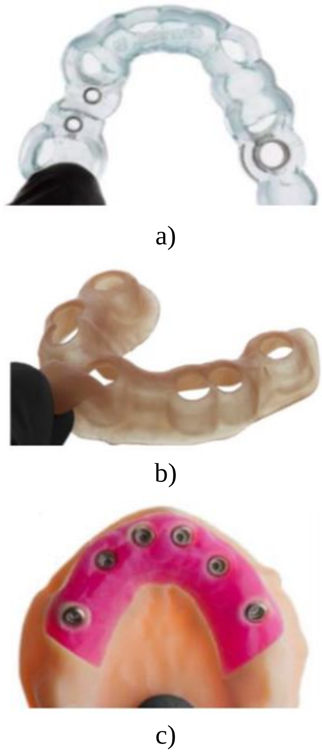

Figure 5. Examples of the use of 3D polymer printing in implant dentistry. a) Surgical guide, b) dedicated tray, c) cast [31].

In tissue engineering, using 3D printing, scaffolds can be made based on the desired dimensions and the porosity amount, surface texture, and total design can be controlled. It is also can add ossification-stimulating factors such as BMP-7 and BMP-2 to stimulate cell attachment and nutrition, blood supply, and proliferation. Cells' direct printing to create tissue eliminates the requirement for scaffolding. Cells are entrusted in layers. Of course, this technique needs more study and investigation and can be helpful for dental tissue reconstruction where the pulp cavity is filled by cells [32].

The emergence of digital technology and 3D has had a significant effect on prosthetic work and tooth reconstruction. By using digital techniques, it is possible to create dedicated trays in a short time, with higher exactitude, and with uniform spacing for molding materials **(Figure 6)** [29].

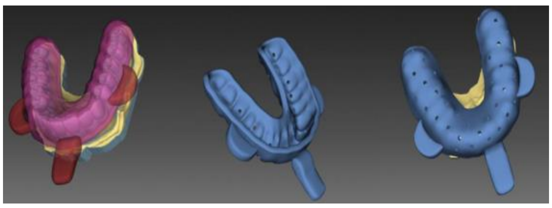

Figure 6. A special tray made by a 3D printing method.

AM methods for making dental ceramics **(Table 1)**
Uçar *et al*. compared the mechanical properties of lithographed alumina, pressed alumina, and milled zirconia [33]. Milled zirconia showed the highest bending strength, followed by SLA Alumina and pressed Alumina, respectively. No significant difference was observed in fracture resistance of SLA alumina and milled zirconia, both were significantly higher than pressed alumina.

Table 1. Methods and materials used for printing ceramics [34].

AM technology	Ceramic type
Stereolithography	Zirconia
	Alumina
Material extrusion	Feldspathic porcelain
	Zirconia
Powder bed melting	Feldspathic porcelain
Inkjet printing	Zirconia
Binder injection	Feldspathic porcelain

This review study has been made to introduce the methods of production of dentures and the current utilization of its different techniques in dental prostheses manufacture. The ASTM (American Society for Testing and Materials) has classified additive structure technology into seven processes based on the printing method. So far, in dental prostheses, there are four methods of stereolithography, SLA (Stereolithography), SLM (Selective Laser Melting), FDM (Fused Deposition Modeling), and Inkjet (Material jetting) for making implants, surgical guides, special trays, casts, cast patterns, movable prostheses, fixed prostheses, and metal frames have been utilized. SLA is the main method utilized in prosthodontics to make cast patterns, casts, temporary prostheses, and complete dentures. Previous research compared SLA accuracy with milling and conventional methods. In the Patzelt *et al*. study, the casts provided by the SLA technique were more stringent than the milled casts [35]. However, the casts provided by milling had an acceptable stringent from a clinical point of view. Based on Jeong *et al*.'s study, printed cassettes were more stringent than milled ones [36].
Based on the study of Davda *et al*. dentures printed using SLA are superior in precision terms and stringent compared to conventional techniques [37]. Based on the findings of the research by Kalberer *et al*. the intaglio (internal surface) of the prostheses cut using the milling machine was more stringent than the one printed using SLA, which may be because of shrinkage before the final polymerization of the printed denture, because in milling utilization polymerized resin, but non-polymerized resin is utilized in printing and needs final polymerization [38]. Kim *et al*. compared the marginal and internal fit of the cast, lathe-cut patterns, and SLA printed [39]. Based on the results, the marginal and internal matching of SLA patterns was clinically admissible and slightly better than casting. The marginal gap amount was higher in milled patterns.
The SLM technique is utilized to print the prosthesis metal frame. The mechanical attributes of Cr-Co frameworks printed using SLM are better than those created by conventional milling or casting [40]. In the process of casting, completely homogeneous alloys are not provided, which causes the frame construction with weaker areas and decreased clinical success. Both SLM and milled frames reveal greater homogeneity, which may reasons for some of the observed stiffness differences. The SLM frame surface roughness is a challenge and can complicate the internal accuracy and peripheral matching. The SLM frame surface is probably affected by the molten metal control resulting from the laser irradiation. The laser beam can melt the powder adjacent to the main structure and can cause surface roughness and nodules.
According to the findings of this study, it can be stated that AM has made a great transformation in the dental prostheses manufacturing field; however, its utilization is still limited. Developments are essential to overcome material and technical limitations. Most of the results are based on laboratory research. Long-term clinical research is required before different 3D printing techniques can be fully implemented in dental prosthesis manufacture.

Conclusion

3D printing has an immense transformative capacity in dentistry. Mass customization, Design freedom, and the ability to print intricate structures with minimal material waste are the main benefits of 3D printing. Currently, with the assistance of this cost-effective method, the wasted materials amount is very small. Surgical guides, mobile prostheses, dedicated trays, casts, metal frames, cast patterns, temporary prostheses, and implants can be produced. According to the results, the prostheses quality made by this method is clinically acceptable.
Future studies are suggested to evaluate the mechanical and structural properties of the materials used in printing as well as their behavior under the influence of thermal changes and mechanical forces. More studies are required to evaluate the dimensional stability and

wear resistance of printed prostheses and compare it with conventional methods. It is also suggested to compare different printing methods to make a type of prosthesis.

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