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Review / Derleme

3D Printers in Prosthetic Dentistry

Protetik Diş Hekimliğinde 3B Yazıcılar

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ABSTRACT

CAD-CAM technology has been used in dentistry for many years. Its advantages over traditional methods include easy manufacturing, accuracy, and variety of restorative materials. While subtractive manufacturing performed with milling units; three dimensional (3D) printers are used for additive manufacturing during the computer-aided production procedure. The additive manufacturing process uses different approaches and a varied range of 3D printers. This review focuses on current 3D manufacturing methods, as well as their applications in prosthetic dentistry.

Keywords: 3 Dimensional printing, Dental prostheses, Maxillofacial prosthesis

ÖZ

Diş hekimliğinde CAD-CAM teknolojileri uzun yıllardır kullanılmaktadır. Geleneksel yöntemlere göre üretim kolaylığı, doğruluğu ve farklı materyaller kullanılabilmesi gibi avantajları bulunmaktadır. Bilgisayar destekli üretim aşamasında kazıyıcılar ile eksiltmeli, üç boyutlu (3B) yazıcılar ile eklemeli üretim yapılabilmektedir. Eklemeli üretim sürecinde kullanılan birçok yöntem ve çok çeşitli 3B yazıcılar bulunmaktadır. Bu derlemede mevcut 3B yazıcılar ve üretim yöntemleri ele alınırken, protetik diş tedavisindeki kullanım alanları açıklanmaktadır.

Anahtar Kelimeler: 3 Boyutlu printing, Diş protezi, Maksillofasiyal protez

Introduction

Computer-aided design - computer-aided manufacture (CAD-CAM) technology was introduced in the 1980s and has shown significant development until today. CAD-CAM systems consist of three parts: Transferring the data to the computer (digital impression), designing the restoration in software (CAD), and manufacturing the restoration (CAM).[1] The widespread use of CAD-CAM technology in dental practice has provided significant advantages over traditional methods, such as the ability to produce dental restorations faster and more precisely, minimize physician or technician-related errors, and improve material quality.[2]

In computer-aided manufacturing, the restoration was designed with software and produced by machining from the selected material. When CAD-CAM technology was first used in dentistry, restorations were produced by milling ceramic blocks.[3] This method, called "subtractive manufacturing" provides well-fitting restorations with high material quality. However, it has disadvantages such as the high amount of material wasted during the milling of the restoration from the block, the high cost of grinding tools, and the potential formation of defects starting from the surface of the material and progressing to the microstructure.[2]

"Additive manufacturing", which is defined as the formation of a 3-dimensional object by making thin layers of liquid or powder material on a 2-dimensional plane, was first developed in the early 1980's by 3D Systems, whose founder was Charles Hull. Additive manufacturing devices, commonly referred to as three-dimensional (3D) printers, have shown great improvements over the years and have been widely used in engineering, medicine, jewelry, architecture, art, archaeology, and education.[4] In dentistry, it was first used in 2013 to produce surgical bone models, models to simulate implant surgery, and surgical templates for implant placement.[3] In prosthodontics, 3D printers aim to eliminate the disadvantages of subtractive manufacturing in the CAD-CAM workflow and are used in model production, construction of fixed or removable prostheses, preparation of wax samples for casting processes, production of impression trays and occlusal splints, and maxillofacial prostheses (**Figure 1**).[5]

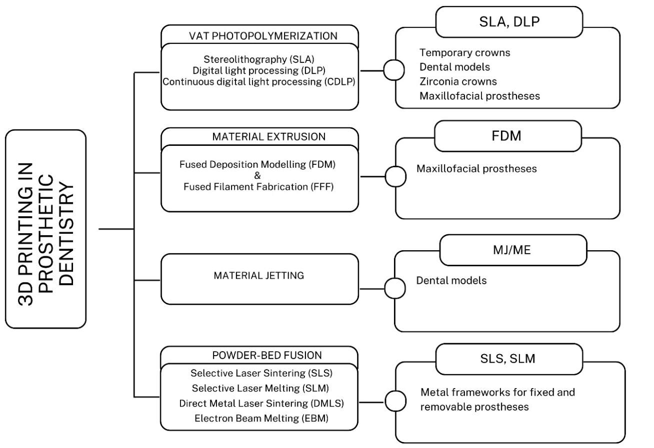

Figure 1. Additive manufacturing methods and fields of use in prosthetic dentistry

Additive Manufacturing Technologies Used in Dentistry

1. Vat Photopolymerization (VPP)
   a. Stereolithography (SLA)
   b. Digital light processing (DLP)
   c. Continuous digital light processing (CDLP)
2. Material Extrusion (ME, MEX)
   Fused Deposition Modelling (FDM)/ Fused Filament Fabrication (FFF)
3. Material Jetting (MJ)
4. Powder-bed Fusion (PBF)
   a. Selective Laser Sintering (SLS)
   b. Selective Laser Melting (SLM)
   c. Direct Metal Laser Sintering (DMLS)
   d. Electron Beam Melting (EBM)

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In additive manufacturing technologies, a model or restoration is created three-dimensionally in software and separated into thin layers to be compatible with the 3D printer, then additive manufacturing is started.

1. Vat Photopolymerization (VPP)

All 3D printers that work with vat photopolymerization technology are based on shaping the object by controlled polymerization of the light-polymerized liquid resin in layers.[6] The basic mechanism of these devices consists of a tank in which the liquid resin is placed, a moving platform, and a light source that enables polymerization. At the end of the process, the object is rinsed with a solvent such as alcohol and placed in an ultraviolet oven to completely harden the resin.[7]

There are different techniques of vat photopolymerization used with liquid resins. Among these techniques, SLA, DLP, and CDLP technologies have frequently been used in dentistry. They showed differences, for example, in the type of light source and the localization of the light.[8]

a. Stereolithography (SLA)

The stereolithography technique was first defined in 1986 as “the construction of solid objects by depositing thin layers of ultraviolet-cured material on top of each other.”[1] In the SLA technique, the controlled polymerization of the photosensitive resin, which is liquid at room temperature, in layers by scanning it with a point ultraviolet laser beam allows the object to be shaped.[6]

b. Digital Light Processing (DLP)

In digital light processing (DLP) technology, a conventional light source is used to photopolymerize the printed object. The 3D printer projects the image of all layers on the platform at once and each point in this image is hardened simultaneously.[9] The DLP method has been reported to be more accurate in producing diagnostic models compared to other types of 3D printers.[9]

c. Continuous Digital Light Processing (CDLP)

CDLP is an advanced DLP technology with the advantage of faster printing time. Unlike conventional additive printing, there is an oxygen-permeable window made of a glass membrane to prevent radical polymerization in this technique.[10]

In clinical practice one of the main differences of 3D printers with vat photopolymerization technology is the production speed. While the light source is a laser in SLA devices, DLP and CDLP devices use a reflected light source. Whereas the laser beam scans and hardens each layer, the polymerization of the entire layer at the same time in DLP devices enables these devices to produce faster than SLA devices.[11]

2. Material Extrusion (ME)

In Fused Filament Fabrication (FFF), also known as Fused Deposition Modeling (FDM), thermoplastic materials in the form of filaments are melted and stacked in layers with the help of a nozzle to shape the object.[8] The use of this method in dentistry is limited because the products have low definition and resolution compared to vat polymerization and require long printing times.[8,12] However, due to its advantages such as being a low-cost method, having a simple mechanism, and very few post-production processes, it has been used in the production of impression trays, diagnostic models, temporary base materials used for the recording of jaw relations, and surgical guides with filaments suitable for medical use.[13]

3. Material Jetting (MJ)

Material jetting is a 3D printing technique that uses a process like 2D printing. The first layer is formed by heating the liquid photopolymerized resin, increasing its fluidity, and spraying it directly onto the platform on which the object will be shaped through the print head, and the layer is polymerized with an ultraviolet light source.[6] This process continues in layers until the object is completely shaped.[14] In the MJ technique, very small amounts of material are placed on the platform and polymerized in each layer, eliminating the need for additional polymerization after production. It is a fast and high-definition production method for resins, and it is possible to produce objects consisting of multiple materials and colors.[14] The dimensional accuracy of MF found higher than the other printing methods, and it is used for production of surgical guides and mouth pieced fixation instruments.[15,16]

4. Powder-Bed Fusion (PBF)

Powder bed fusion techniques are based on the principle of melting and fusing powdered material with a laser or electron beam to form an object.[4] In all PBF techniques, the powder is spread on the first layer, the heat generated by the laser beam hitting the surface and brings the powder together in the desired shape then the object is shaped in layers. After the sintering process is completed, the produced part is cleaned of dust. With these printers, there is no need for an additional support material as the powder outside the sintered parts acts as a support.[4]

While SLS technology can shape a variety of materials such as metals, ceramics, plastics, and wax; DMLS, SLM, and EBM are the only methods used to shape objects by melting metal powders.[9] Materials formed by PBF have very high strength and good mechanical properties.[17] The high resolution and excellent printing quality of powder bed fusion technologies allow the production of fine and complex structures. As a result, their use in dentistry has become widespread, and eventually they may have replaced cast metal restorations.[18] The major disadvantages of this technique include surface roughness, internal porosity, slow production, and high cost.[18,19]

3D Printer Applications in Prosthodontics

1. Crown and fixed partial restorations

Additive manufacturing with 3D printers is used in many stages of fixed prosthetic treatments. These include the fabrication of provisional restorations, preparation of working models, fabrication of full ceramic restorations, and framework for metal-ceramic crown and bridge restorations.

Provisional restorations

Temporary restorations are used during fixed prosthodontic treatment to meet cosmetic, functional, and biological needs. The success of traditional temporary restorations is dependent on the technician's experience and skills. Errors in production can result in voids in the material mass, compromising its mechanical qualities and causing restoration fractures. Currently, 3D printing is widely used to produce provisional restorations.[20] Since 3D scanning, design, and fabrication have become so popular, studies have been done to evaluate temporary restorations made with 3D printers.[21] It has been reported that additive manufacturing with 3D printers is faster, more cost-effective, and more precise method of temporary restoration production than subtractive manufacturing technology.[2,21] Stereolithography (SLA) and digital light processing (DLP) techniques are 3D manufacturing technologies frequently used in the production of provisional restorations from photosensitive resins.[20]

Dental models for prosthetic restorations

Creating the working model, or precise and clear replication of the teeth and surrounding tissues is essential for the laboratory phases of prosthetic restorations. For this purpose, the standard method applied from the past to the present is to take an impression from the mouth and obtain a model by casting a model material suitable for the impression. In dentistry, these models-achieved through proper material selection and technique- have been accepted as the gold standard.[8]

However, errors related to the properties and application techniques of impression materials and casts can adversely affect the accuracy of traditional impressions and models, resulting in the misfit of prosthetic restorations. Challenge of storing the casts and degradation over time are two additional disadvantages.[8] Many difficulties have been overcome by 3D scanning and 3D printed models, resulting in their widespread use in dental practice. Despite advances in 3D printer technology, research on the accuracy of printed and conventional gypsum models, which are critical in prosthodontics, is still ongoing. Some studies evaluating the accuracy of traditional, and 3D printed models have reported that the average error in traditional models is consistently lower than that of their 3D printed counterparts.[8,22] On the other hand, studies comparing traditional models and the 3D printed models produced with MJ and SLA methods reported that there was no statistical difference in terms of accuracy.[23] When the studies evaluating the accuracy and clinical use of the models obtained with three-dimensional printers were examined, it was reported that they were acceptable for orthodontic applications, but sufficient accuracy was not always achieved in prosthetic restorations requiring high precision.[8]

Substructure of metal-ceramic restorations

A good marginal and internal fit are crucial for mechanical stability and soft tissue health in crown and bridge restorations. Cast metal substructures are produced with a traditional process that determine the fit of restorations. When appropriate clinical and laboratory steps are followed, these methods produce very well-fitted substructures.[24]

With the widespread use of computer-aided manufacturing methods in dentistry, the preparation of metal substructures with additive and subtractive methods has become popular. Although subtractive manufacturing is a production method that provides high precision in metal substructures[9], it has disadvantages such as surface finish, limited material option and high cost.[9] In metal substructure production, additive manufacturing saves material and time and has been found to simplify the fabrication of complex structures.[9]

Zirconia restorations

With the introduction of CAD-CAM technology in dentistry, zirconia could be processed and used as a restorative material. The first zirconia blocks were used as substructures for glass-ceramic veneers due to their high mechanical strength and high opacity. Monolithic zirconia restorations fabricated by milling are a reliable treatment option in modern prosthetics, as demonstrated in several clinical studies.[25] However, there are drawbacks such as the generation of a significant amount of post-milling waste and bur wear, especially when milling the fully sintered blocks.[26] These blocks are dimensionally stable however milling process can create microcracks on the ceramic surface, which can affect the long-term performance of the restoration.[26] Currently, most CAD-CAM systems use pre-sinterized blocks to fabricate zirconia restorations. The milled restoration, which is an enlarged size, is subjected to sinterization process. This production method has a certain advantage of the easy milling of pre-sinterized blocks. Furthermore, surface defects and microcracks are minimized with sinterization process. [25]

Recently, rapid developments in 3D printers led to additive manufacturing of dental zirconia restorations. Following the production of ceramic parts using additive manufacturing in 2000, zirconia dental prostheses were produced using direct inkjet printing for the first time in 2009.[27] However, 3D-printed dental zirconia materials are still in their initial stages and many researchers are working on the performance of 3D printed zirconia and comparing them with milled zirconia.[27] Currently studies indicate that 3D printed zirconia has a similar microstructure, phase composition, and mechanical properties with blocks. On the other hand, slightly inferior mechanical properties were also reported for 3D printed zirconia.[27] In a recent in vitro study, Wang et al.[28] compared the marginal and internal discrepancies of monolithic zirconia crowns fabricated by SLA and milling methods. They reported that the discrepancy of restorations fabricated by SLA was compatible with those fabricated by milling.[28] In a study by Revilla Leon et al.[29] milled monolithic zirconia crowns had the least marginal and internal inconsistencies compared to 3D-printed crowns.

Zirconia restorations are made using additive manufacturing processes such as SLA, DLP, FDM, and binder jetting, of which SLA and DLP are currently the most used methods. The raw materials characteristics, the printing conditions, the debinding, sintering, and other post-processing steps all affect the mechanical qualities and accuracy of zirconia products that are produced by additive manufacturing technologies. Research is going on the accuracy and mechanical characteristics of additive manufacturing zirconia materials.[27]

2. Removable partial denture frameworks

Conventional fabrication of removable partial denture (RPD) frameworks includes the gypsum cast fabrication from the dental impression, surveying, designing, waxing up the framework and then casting into a cobalt-chromium (Co–Cr) framework.

3D printing technology which revolutionized digital dentistry also took place in fabrication of removable partial prosthetics. Two primary additive techniques have been commonly used for RPD production: CAD design of the RPD framework is 3D printed using a castable resin, which then can be invested and cast into a Co–Cr framework, and direct printing of the metal framework using selective laser melting (SLM).[30] The main advantage of this method over the conventional method is the option to trial frameworks in patients or on the cast and make modifications before casting. However, this step may lead to direct distortion of the framework, therefore reprinting may be required.[31] Direct metal printing technique of RPDs is a faster and technically more advanced procedure, however, its emergence as the new standard remains uncertain.[31] However it is reported that the complete digitalization process showed the lowest misfit in comparison to a conventional method.[31] In another recent study, SLM-printed frameworks achieved an acceptable adaptation however, frameworks with a large span and relatively more retainers and clasps showed better adaptation when fabricated with the casting technique.[32]

3. Complete removable dental prostheses

The complete removable dental prostheses (CRDPs) are conventionally made from the polymer polymethyl methacrylate (PMMA) using the conventional flasking technique, which has been a proven technique for decades. In recent years, the fabrication of CRDPs by CAD-CAM method has gained popularity in both clinical and laboratory practices.[33] Today, variety of materials are available in the market for the fabrication of digital CRDPs.[34] There are two digital fabrication techniques for CRDPs; the subtractive and the additive.[35] In the subtractive technique, the denture base is milled from a pre-polymerized PMMA blank then prefabricated or milled denture teeth are bonded on this denture base. However, a considerable amount of material is wasted in this technique. With the more recent additive manufacturing technique, less denture resin material is used. Comparing conventional, subtractive, and additive fabrication techniques of CRDPs; CAD-CAM milled CRDPs show similar or better fit of the intaglio surfaces, equal biocompatibility, and improved mechanical properties than conventional dentures.[33] Regarding the accuracy of dentures, there are no clear conclusions about the superiority of CAD-CAM milling and 3D printing.[36] A recent study evaluating the adaptation of milled and 3D printed dentures reported that milled denture bases fit better in the overall and primary stress-bearing areas than 3D printed dentures, while 3D printed dentures appeared more accurate in the peripheral seal area, which had a minor undercut that is not suitable for milling technology.[37] Clinical studies were also performed to evaluate the functional results of 3D printed CRDPs, and they revealed comparable or higher patient and clinician satisfaction compared with conventional dentures.[33] Satisfying clinical results may be related to the advantages of digital workflow such as saving working time, more comfortable impressions, and securing patients' records. However, the strength, esthetics, and material biocompatibility remain questionable the issues.

4. Extraoral maxillofacial prostheses

The conventional methods for making facial prostheses include multiple stages and require intensive labor and time. Also, these prostheses need to be renewed at regular intervals because of their limited lifespan of about 2 years.[38] The use of digital methods in the fabrication of facial prostheses shortens clinical and laboratory stages and provides comfort to the patient. Facial prosthesis fabrication using CAD-CAM technology includes data collection from the defect site, design of the prosthesis, and production stages. Data collection can be performed with various imaging methods ranging from CT scans to digital cameras.[39] Then, the prosthesis is designed using appropriate software. Production of the prosthesis is performed in two ways using 3D printers; direct or indirect printing. The direct method includes printing the final prosthesis from silicone in a 3D printer. The indirect method includes printing the negative mold in which the silicone will be packed or printing the pattern of the prosthesis which will be used for gypsum mold fabrication.[40]

Directly printing the silicone prosthesis can be carried out by inkjet printing (binder jetting) method by using silicone powders developed for printing maxillofacial prostheses.[41] In the inkjet printing method, the silicone powders are bonded to each other with an adhesive to form a 3D object in layers. The product is then infiltrated with a liquid phase material to fill the gaps and a more durable final product is formed. Another method used for direct prosthesis printing is material jetting.[42] With this method, products containing both hard and soft parts can be obtained using polymers as raw materials.[43] Also SLA and DLP 3D printing methods can be used in the fabrication of direct facial prostheses from polyurethane-silicone copolymer. Direct production of the facial prosthesis with a 3D printer allows for faster production than traditional methods.[44] However silicone material does not yet have properties suitable for 3D printing like resins so direct printing silicone prostheses have some disadvantages. The availability of limited color shades, the rapid deterioration of the material in terms of mechanical properties and color, and unfavorable surface characteristics of printed silicone limit the use of this technology in the direct fabrication of maxillofacial prostheses.[43]

In the indirect method, a pattern of the prosthesis is obtained using a 3D printer. This pattern is used to create wax assembly of the prosthesis which is tried in the patient and used to fabricate a conventional gypsum mold. Another indirect 3D fabrication technique is printing the mold in which silicone will be packed. For the indirect fabrication of facial prostheses in the 3D printer; SLA, DLP, and FDM are used to print prosthetic parts from resin material.[45]

5. Intraoral maxillofacial prostheses

For the fabrication of intraoral defect prostheses, additive manufacturing provides advantages compared to traditional manufacturing and subtractive manufacturing methods. While CAD-CAM base plates shaped from blocks show very high tissue compatibility in complete denture base plates, the complex and mostly undercut structure of defect prostheses makes milling difficult.[46] In addition, considering the generally bulky structure of obturators, the high polymerization shrinkage of traditional heat-polymerized resins, and the insufficient size of CAD-CAM blocks, additive manufacturing is an easy and economical alternative.[47,48] In the literature; 3D printing technologies of SLA, DLP and FDM were used for the fabrication of dentures restoring intraoral defects from the materials of resins and PEEK.[49-52]

Post-processing procedures of 3D-printed dental restorations

After 3D printing of dental restorations, the conversion of monomers to polymers is incomplete and post-processing steps are necessary. Cytotoxic or allergic effects of the residual monomers can have on human cells is known.[53] The first post-processing procedure is washing the 3D-printed restoration in a solvent to remove uncured resin from the surface. For washing procedures, isopropyl alcohol which has been shown not to affect the flexural strength of temporary resins is commonly used.[54,55] Also tripropylene glycol monomethyl ether has been suggested to enhance the accuracy and precision of polymers.[56] The washing method as well as solvent type is important in removing residual monomers. In a study, ultrasonic bath was found to be more effective than a rotary washer or simple immersion in the solvent for eluting residual monomers.[54] Currently, the systems widely use ultrasonic bath with an alcohol solution to remove uncured resin.

After washing, the degree of conversion (DC) in 3D printed polymers is enhanced through UV light-polymerization chambers. The duration and intensity of UV polymerization might affect the mechanical and optical properties of the polymers and improve DC.[53,57] Studies showed that increasing UV time does not have significant effect on the flexural strength and the surface accuracy of an acrylic-based resins.[58,59] Because different resins have distinct chemical compositions, the post-curing process can have varying effects on them. By testing several approaches on the same material, the impact of post-process stages on the mechanical and optical properties of resins was investigated.[54,60,61] Research is required to compare resins with varying compositions and assess the effect of post-processing procedures.

Conclusions

CAD-CAM technology has currently become an integral part of dentistry, especially in prosthodontic applications. In manufacturing, the transition from subtractive to additive has come to the forefront due to its advantages such as increased precision, rapid production, and reduced material consumption.

To be able to fabricate prostheses with high clinical success with the use of 3D printers; the selection of an ideal 3D printer system and material is required as well as the application of an appropriate post-processing application.

Current studies on 3D printers and materials, which are a new and ongoing production system compared to traditional production methods and subtractive production methods, should also be followed.

Değerlendirme / Peer-Review

İki Dış Hakem / Çift Taraflı Körleme

Etik Beyan / Ethical statement

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It is declared that during the preparation process of this study, scientific and ethical principles were followed and all the studies benefited are stated in the bibliography.

Benzerlik Taraması / Similarity scan

Yapıldı – ithenticate

Etik Bildirim / Ethical statement

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