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Revolutionizing Dentistry: Comprehensive Review of 3d Printing Techniques & Uses

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ABSTRACT

The advent of 3D printing technology has ushered in a transformative era in dentistry, offering unprecedented opportunities for innovation and advancement. This comprehensive review explores the diverse applications of 3D printing in dentistry, encompassing the fabrication of dental prosthetics, implants, surgical guides, and anatomical models. We delve into the various 3D printing techniques, including stereolithography, fused deposition modelling, and selective laser sintering, evaluating their merits and limitations. The article also scrutinizes the evolving landscape of materials used in dental 3D printing, highlighting the latest developments and their impact on clinical outcomes. Furthermore, we discuss the current challenges and future prospects of 3D printing in dentistry, addressing regulatory considerations and potential avenues for continued growth. This review serves as a valuable resource for dental professionals, researchers, and policymakers seeking a comprehensive understanding of the revolutionary impact of 3D printing on the field of dentistry.

KEYWORDS: 3D Printing, Rapid Prototyping, Stereolithography, Additive Manufacturing, Resins..

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INTRODUCTION

Dentistry, has a long history of serving the needs of patients by offering dental restorative and prosthetic devices to recover patients' oral function and maintain their health. In past time the treatment modalities were carried out in traditional way using conventional techniques and machineries. With increasing demand of safe and aesthetically pleasing prosthesis there has been advancement in materials as well as fabrication techniques. One of the highly praised and disruptive technology which shall revolutionize manufacturing process is 3D printing. [1]

In 1986, Charles Hull introduced the first three-dimensional (3D) printing technology.[2] In 1986, Stereolithography (SLA) was patented by Hull and built and developed a 3D printing system. In 1990, Scott Crump patented fused deposition modelling (FDM).[3]Since then, 3D printing has been progressing throughout. Combined role of oral scanning, CAD/CAM designing and 3D printing methods has led to manufacturing of products of desired complex geometry which was not feasible with conventional techniques.[1] CAD/CAM system has three domains: data acquisition or scanning, computer aided designing, computer aided manufacturing. In dentistry currently CAM systems are based on subtractive approach.[4] In the manufacturing step, a fast-growing alternative to milling methods is three-dimensional (3D) printing.[2]

The concept of 3D printing is also referred to as additive manufacturing (AM) or rapid prototyping (RP) and also solid-freeform technology (SFF).[3] Additive manufacturing is building the material layer by layer using different techniques from the digitally acquired data. The digital data is acquired by intraoral scanner or lab scanners and printed using 3D printers.

3D PRINTING PROCESS [5]

Acquisition of 3D patient model

(Physical or Digital Model)

↓

Creating Design

Model/Prosthesis designed in CAD software

↓

Preparing the Model for Printing

When necessary, support structures are designed in the software and the structure is 'sliced' to create a stack of layers.

↓

3D Printing

The sliced data is sent to the printer, where material is laid down layer by layer fashion

↓

After Processing

Removal of support/Sandblasting/Jet washing/Grinding/Heat treatment (For metal objects)

According to by the American Society for Testing and Materials (ASTM) Additive manufacturing is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies."[6] With the rapid evolution of new materials, printing technologies and machineries, rapid prototyping is likely to completely change the traditional teaching and experimental modes .[7]

Advantages of 3-D Printing.

With comparison to traditional wax loss technology and subtraction computer numerical control methods, 3D printing has advantages in process engineering.[8]

1. Enhanced treatment procedures
2. Patient treatment becomes fast, smooth and with greater precision
3. Dependably superior appliances [9]

Its ability of fast production, high precision and personal customization, complete dentures and implant teeth are easier to fabricate.[10]

Also, the applications of 3D printing in dentistry can reduce the cost of treatment and provide more personalized services and simplify the complex workflow related to the production of dental appliances.[11]

The 3D printing technologies can quickly accept CAD data. Also, it can rapidly manufacture single and small-batch parts, new samples, complex shape products, moulds and models.[12]

Materials used to print 3-D objects

CAM uses computer-generated paths to shape a part.[13] Early systems relied almost exclusively on cutting the restoration from a prefabricated block with the use of burs, diamonds or diamond disks. The material should have variety, different in composition, good strength and able to perform finishing procedures on it.

Most of the raw materials for additive manufacturing used for dental and medical purposes may be categorised into binder/powder material combinations including polymers (including resins and thermoplastics), ceramics and metals.[2]

Polymers

3D printing machines use polymers as the raw material for building programmed structures.

Thermoplastics-Used in fused deposition model (FDM) technique, where filaments of the thermoplastic material are heated then extruded through the nozzle to build desired precise structures. Examples are acrylonitrile butadiene styrene (ABS) and the eco-friendly polylactic acid (PLA) polymer.[14] Recently Thermoplastics-infused biodegradable polyester with bioactive tri-calcium phosphate has been shown to be a promising prospect for use in building tissue scaffold structures in dentistry.[15]

<u>Wax</u>- polymer commonly used in additive technique.[2] Various techniques use it as support material for built. Also used as a build material for wax-ups of complex prosthodontic cases.[6]

<u>Photoinitiated Resins</u>-Used in Stereolithography (SLA) technique. It is cured one layer at a time using UV light. They can be mixed with biocompatible material like bioactive glass. These polymers impart much more flexibility in color, rigidity and modification of components.[2] Light-cured resins may also be used as a substitute for the manual wax-up step in the lost-wax casting process,[2] which can create equally precise final structures once invested into a mold for casting.[16]

Ceramics

Ceramics are used in various techniques of additive manufacturing. These include SLA, SLS, FDM, inkjet 3D printing.

Use of SLS technology to produce ceramics involves either ceramic powder or a pre-sintered ceramic.[2]Till date, however, direct SLS of ceramic powder has only yielded porous structures difficult to post-process to high density, so it has been mainly used to produce modified glass-ceramics for fabrication of bioactive tissue scaffolds.[17] Another additive technique, involving powder-bed inkjet 3D printing and vacuum infiltration, has been found to produce dense alumina-reinforced-ceramic structure with high density and satisfactory strength.[18]

Dense alumina-reinforced ceramic structures were also successfully and fabricated with alumina loaded with photo-initiated resins in SLA machines. This technique is a promising one, because SLA machines are considered as one of the most accurate additive technologies currently available.[19] FDM and the use of a jetted binder to bind specially coated ceramic powders together to produce the green form of the ceramic is then sintered to achieve full strength. [20]

Metals

SLS additive technique uses following for production of metallic structures - titanium, CoCr, and nickel alloys. There have been many well-designed studies on the properties of titanium alloy (particularly Ti6Al4V) fabricated using SLS but very little has been produced on other materials that may be produced using the same technology.[21]

Additive manufacturing is a promising method of CoCr production. Previously, SLS-based machines produced rather weak and porous structures that required extensive post-processing.[22] A variation of the above technique, called direct metal laser sintering (DMLS), has promising dense end products.[2]

THREE-DIMENSIONAL PRINTING TECHNIQUES

According to different working principles, 3D printing technologies can be divided into three categories:

A. Powder bed fusion.
B. Light curing.
C. Fused deposition modeling.[7]

As shown in Table 1, they can be refined into specific technologies, each with its distinctive advantages.

Table 1.

hniques	ssification	terials	vantages
der bed fusion	M S M ILS	tal materials[23]	ed no de-binding process[2] table for metal[24] d-products are dense[25]
ht curing	A P	in [26] amic [11]	od mechanical resistance [3] s construction time [3] her surface quality of manufactured objects [11]
ed deposition modelling	rmoplastic materials [24]		compatible and better mechanical strength of fabricated scaffolds [27]

Classification based on different working principles and related techniques.

SLM- Selective laser melting
SLS- Selective laser sintering
EBM- Electron beam melting
DMLS- Direct metal laser sintering
SLA- Stereolithography
DLP- Digital light processing
PJ- Photo jet

A. Powder bed fusion.

Suitable material for laser sintering or fusion technologies is any powdered material, which can be sintered or fused by laser radiation and solidified by cooling.[28] According to the powder materials and energy sources, PBF is divided into the following printing technologies:

1. Selective laser melting (SLM)
2. Selective laser sintering (SLS)
3. Electron beam melting (EBM)
4. Direct metal laser sintering (DMLS)[29]

All these technologies use heat to melt powdered materials.[30] In dental application, PBF is used to manufacture all types of metal products including AM titanium

(Ti) dental implants, custom sub periosteal Ti implants, custom Ti mesh for bone grafting-techniques, cobalt chromium (Co-Cr) frames for implant impression procedures and Co-Cr and Ti frames for dental implant supported prostheses.[30] Moreover, PBF shows considerable potential for producing ceramic restorations [31], which can be used to manufacture crowns, model casting abutments and models.

SLS/ SLM/DMLS

Selective laser sintering (SLS) is a system wherein a high energy beam laser is used to induce fusion of the powdered raw material.[32] The laser creates a solid layer out of the powder. The platform will be lowered to make space for the laser to sinter the next layer of powder. This technique of structure creation does not require additional material support during printing because support is provided by the powder surrounding it.[33]

Study models, guides for drilling and cutting as well as metal frameworks can be created using SLS.

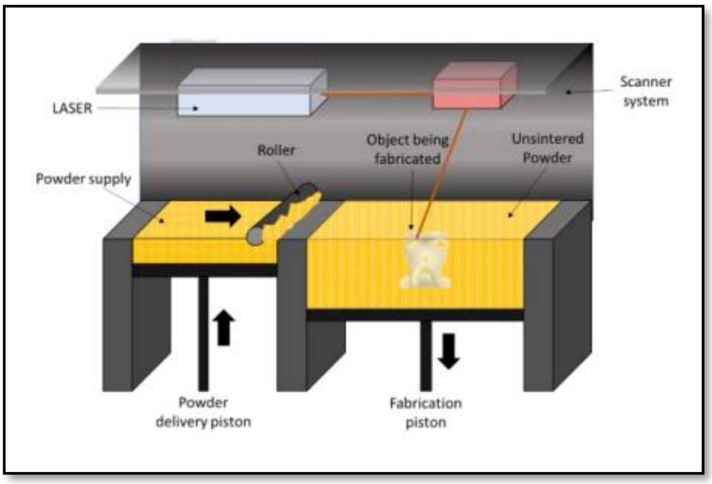

Figure 1: Selective laser sintering (SLS).[33]

The advantages of SLS include the use of autoclavable materials, mechanically functional printed object, reduced production cost with increase in production volume.

The disadvantages of this printing method are the health risk associated with inhalation of the powdered raw material, the initial high cost in start-up and the need for supplementary supplies such as compressed air for proper functioning of SLS .[34,35,36]

The function of the laser is to increase the temperature of the powder to close to, but not its sintering point. This sintering process converts the solid power into a semi-liquid state. The platform on which the first layer forms lower by ~0.1 mm, giving the laser space for a new layer of powder to be sintered. This stepwise sintering and fusion continue until the object is fully printed. The object is kept to cool down after printing is complete.[35]

Another benefit of SLS is the almost utilization readiness of the printed object. Whereas other printer technique requires an extra sanding step or other forms of finishing before the printed products are usable, this step is usually not mandatory for the SLS technique. As SLS printers does not require structural support during printing, the processing time is considerably faster when compared with SLA and FDM.[37,38,39]

Three types of SLS printing are available:

1. metal-based
2. ceramic-based
3. polymer-based SLS.

The metal-based SLS technique requires fine metal powders, whereas the polymer-based SLS technique utilizes fine-grained thermoplastic polymers as raw materials.

For metal-based SLS, different metal powders may be employed, such as stainless-steel alloys (316, 304L, 309, 174), and titanium alloy (6AI-4V).

Unlike polymer-based SLS which does not require gas injection, metal-based SLS requires protective gas to be flooded into the printing chamber to avoid oxidation of the metal powder when the latter is heated to a high sintering temperature.[32]

Selective laser sintering (SLS) - for metals and metal alloys is 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 connect objects to build platform.[5]

B. Light Curing.

Light curing technology is a general term for a type of 3D printing technologies which uses photosensitive resin materials that are cured and moulded under light irradiation.[40]

It consists of three main technologies:
1. Stereolithography (SLA)
2.Digital light processing (DLP)
3.Photo jet (PJ).

The printing process in SLA and DLP technologies can be divided into three discrete procedures:

i. light exposure
ii. building platform movement
iii. resin refilling.[7]

SLA

Stereolithography (SLA) is the first commercially available 3D printing technology. This 3D printing method involves photoinduced polymerization to create layered structures using highly cross-linked polymers.[41]

This technology may be subdivided into different categories based on the type of platform motion and laser movement. Printing proceeds through three major steps: light/laser exposure, platform movement, and resin refilling.[33]

Stereolithography is the typical representative of AM, which consists of layer-by-layer modelling. A 3D digitized model, which acts as the template for the fabrication process, guides the SLA machinery to complete the printed object. The layers are bound together bottom-up upon exposure of the resin to ultraviolet light, which induces free radical polymerization (FRP) of the resin monomers. As one layer is polymerized, the resin platform lowers by a distance equal to the thickness of one layer and builds the next layer until the printing of the digitized 3D object is completed. The discontinued manner of processing can be overcome by combining SLA with continuous liquid interface production.[42,43]

Variables such as light source intensity, scanning speed as well as the amount of resin monomers and photo initiators may be controlled to obtain the required modelling kinetics and properties of the final product. [44]

Presently, SLA is applied in the manufacturing of temporary and permanent crowns and bridges, temporary restorations, surgical guides, templates, and dental model replicas.[45]

Stereolithography accommodates flexibility in design, geometric shape and scaling, resulting in highly accurate personalized devices. High precision measurements retrieved from the patient's scanning data enable production of reliable appliances for prolonged use .[46]

However, cytotoxicity of the printed appliances may be caused by the leaching of residual unreacted resin monomers from the printed appliances. They may affect the longevity of the appliances.

Stereolithography demonstrated greater clinical accuracy than other digital/analog methods in the production of dental stone casts; the 3D printing technique represents an acceptable substitute for diagnosis, treatment and production of prosthetic devices.[47]

Nevertheless, SLA-printed dental devices suffer from poor mechanical properties caused by the selective choice of resins that can be photopolymerized .[48]

Nanoparticle incorporation into the polymeric matrix improves mechanical properties.[49] Other coupling agents such as ceramic fillers protect the printed structure from fracture by improving stress distribution. Antimicrobial agents have also been incorporated into the resins to address the hurdle of microbial colonization of oral devices .[50,51]

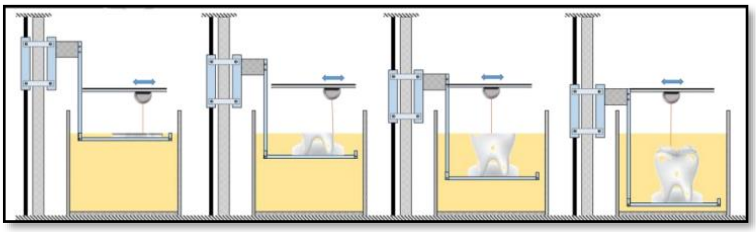

Figure 2. Layer by layer printing process by Stereolithography[33]

Digital light processing (DLP)

DLP is a photocuring technology which is similar to SLA process. The materials are liquid photosensitive resins which undergo photocuring and subsequently form the 3D printed part layer by layer. The first layer is formed on the build platform. Based on the position of the UV source, the build platform may be in ascending or descending direction.[52] Next layers will be formed on their previous layers.

DLP 3D printer utilizes a digital projector screen to flash the current layer's image, through a transparent bottom/top of the resin tank, across the build platform or previous layer. After curing each layer, the build platform goes either up or down as the thickness of a layer until completing the entire part .[53,54]

A digital micromirror device (MDM) is used to reflect the light. DMD consists of a matrix of microscopic-size mirrors. These mirrors direct the light from the laser projector to the projection lens. They make different configurations, adjustable for each layer, such that they create the 2D sketch of the layer by light on the curing surface.[55]

Although SLA and DPL are very similar, they also have some differences. The main difference being the light source. SLA benefits from UV laser beam while DLP uses UV light from the projection source. Consequently, in SLA laser beam moves from point to point and cures the resin from point to point while in DLP the light source is stationary and cures each layer of the resin at a time. These different curing processes result in more precise and better quality in SLA compared to DLP, while on the other hand improves the printing speed in DLP method. The intensity of the light source in the DLP 3D printer is adjustable while it is not adjustable in the SLA printer. This means that the operator can control the effect of light on the resin. In summary, DLP is advantageous in the fast printing of bigger parts with fewer details while SLA is advantageous in printing accurate parts with better details .[56,57,58,59,60]

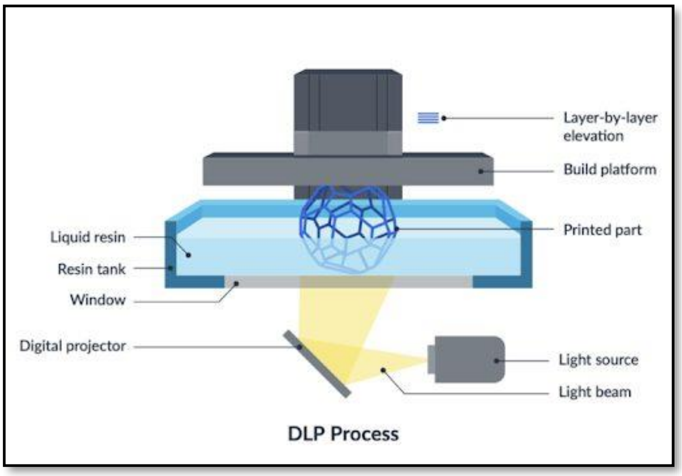

Figure 3. Direct light processing

Photo jet (PJ).

Unlike the above two patterns of polymerizing liquid monomers and oligomers at specific locations, the principle of PJ is a photopolymerizable inkjet. During the printing process, the print head moves along the X/Y-axis and the photopolymeris sprayed on the table, while an ultraviolet lamp emits light along the direction of movement of the print head to cure the photopolymer on the building surface to finish one layer of printing.

The table then descends one layer along the Z-axis and the device repeats the build cycle until the object is printed. The distinctive feature of this technology is the diversity of materials used; from thermoplastics to resins and ceramics, even zirconia paste. All the materials listed can be printed and fused, which is a unique advantage over other technologies. Also, inkjet-based 3D printing allows for the blending of materials by printing different materials in the same position, by which it can form objects with a variety of properties.[4]The surface quality and print resolution of the objects manufactured by photopolymer injection technology are particularly high and do not require any small layer thickness for surface polishing. [7]

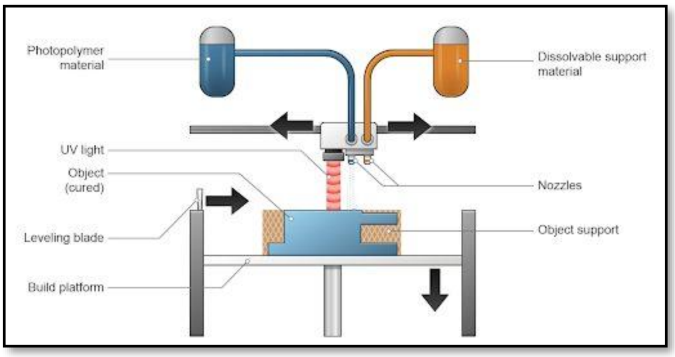

Figure 4. Photo jet process

C. Fused Deposition Modeling

Fused deposition modelling (FDM), also known as fused filament fabrication (FFF), is the trade name for a polymer, composites, or metal alloys softening process that was invented over 20 years ago. It is the second most commonly used rapid prototyping technique, after SLA. [61]This method is remarkably cheaper than the other AM techniques .[62]The basis of this technique is the principle of strand extrusion: the desired type of thermoplastic materials, shaped as strands, is delivered to the extruder. Upon softening, the heated viscous plastic is deposited by an extrusion head those results in layer-by-layer building of the digitized model .[63,64]

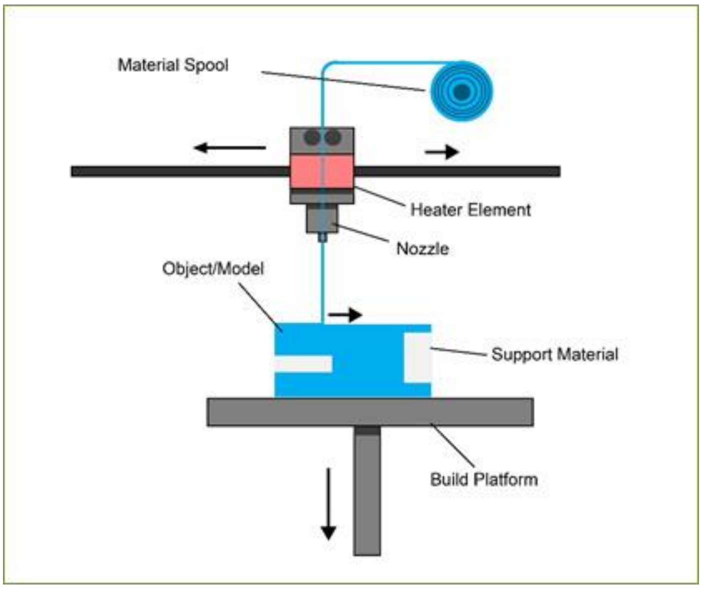

Figure 5. Fused Deposition Modeling Process

Unlike SLA, individual layers within the object have reduced bonding and thus, the final product has greater anisotropy.[42]Thermoplastic polymers and their composites (e.g., acrylonitrile-butadiene-styrene (ABS), polycarbonates and polysulfones) along with low melting temperature metal alloys (e.g., bronze metal filament) are the most common employed FDM filaments.[62,65]

Polymers may be filled with metal (nano)particle reinforcement to prepare (nano)composite filament to improve different features, e.g., thermal resistance and mechanical properties. Mechanical properties in the FDM method can be affected by three main groups of parameters: print material, structural parameters (i.e. rasters angle, infill density, print orientation, and stacking sequence), and manufacturing parameters (i.e. extrusion temperature and rate, layer time, nozzle transverse speed and bed temperature).[62]Because of the weak mechanical properties of these unfilled thermoplastics, FDM is used only for the printing of temporary crowns and bridges in dentistry. Like in SLA, processing commences with the acquisition of computer-aided design (CAD) images. Based on these digitized images, FDM is capable of rapid printing of the desired product.

Fused deposition modeling is the technology utilized in most cheap 'home' 3D printers. It enables the printing of crude anatomical models without too much complexity. Although the final product is brittle and contains rough surfaces, FDM is low cost than other 3D printing techniques. This technique is used in machines with low maintenance and in scientific research.[61]

Table 2 describes the printing system, material characteristics, materials, advantages, disadvantages in detail.

3D/ 4D printing system	Material characteristics	Materials	Advantages	Disadvantages
Stereolithography (SLA)[50,66,,67,68]	Light curable resin	Epoxy and methacrylate monomers	- Product resolution - Efficiency - Reduced working time	- Over-curing - rough surface - Limited mechanical strength - Irritant
Selective laser sintering (SLS)[34,35,36,69]	Powder	- Polymers - Ceramics - Metals	- Structures are fully self-supporting - Protective gas in not needed - large variety of materials can be selected - less to no thermal stresses are accumulated on the component - Components exhibit excellent mechanical properties - Relatively rapid method	- Sample surfaces appear porous and rough - Harmful gases release during fabrication - Relatively highMaterials waste -Expensive Raw powders - Post-processing is often expensive and tedious
Fused deposition modeling (FDM)[65,70,71,72,73]	Thermoplastic polymer and composites, low melting temperature metal alloys	- Paste - Wire	Filaments are cheap and arrive in various colors - Easy to change materials - Maintenance is Cost-effective - Capable of rapid production of shelled structures - Fundamental for thinner layers up to 0.1 mm thick - Released fumes are not toxic	The seam between layers is visible - Discontinuous extrusion results in formation of defects - Some cases require support structure -Delamination between layers may occur due to low extrusion temperature - Printed component may curl off the build platform because of induced thermal stresses
Photopolymer jetting[45,74,75,76,77]	Light curable resin	Biocompatible (MED610) - VeroDentPlus (MED690) and VeroDent (MED670)(all are natural looking medically - approved photopolymers)	- High resolution due to thin layer printing (~16 microns per layer) - Short working time - Excellent surface features - post-modification not required. - Supporting wide range of materials	- Irritant - High cost
Powder binders[77,78]	Materials which are available in powder	- Metal - Ceramic - Plastics	- Safe material - Short working time - Suitable mechanical performance - cheap	- Low resolution - Low strength - Can't be soaked/heat sterilized
Digital light projection[79]	Light curable resin	- Resin	- High complexity and excellent surface finish - small timeframe - Good accuracy - Smooth surfaces	- Limited material selection - Photocurable resin can cause skin sensitization and maybe irritant by contact

Table 2.Printing system, material characteristics, materials, advantages, disadvantages.

Application

thod	plications	ference
reolithography	nporary and permanent crowns nporary bridges nporary restorations gical guides and templates ntal replica models	82,83 85
ective laser sintering	stom-made dental implants rtial dentures	88,89
ed deposition modeling	nture flasks es uth guards l drug delivery device	
otopolymer jetting	nporary crowns ntal replica models	93,94
vder binders	dy casts	
ital light projection	nporary and permanent crowns movable dental prosthesis	97

Recent applications of 3D printing in dentistry is described in Table 3.

Table 3. Recent applications of 3D printing in dentistry.

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