# COMPUTERIZED TECHNIQUES USED FOR 3D PRINTING IN PROSHODONTICS. A SYSTEMATIC REVIEW.

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## Abstract

3D and 4D printing are cutting-edge technologies for precise and expedited manufacturing of objects ranging from plastic to metal. Recent advances in 3D and 4D printing technologies in dentistry and maxillofacial surgery enable dentists to custom design and print surgical drill guides, temporary and permanent crowns and bridges, orthodontic appliances and orthotics, implants, mouth-guards for drug delivery. In the present review, different 3D printing technologies available for use in dentistry are highlighted together with a critique on the materials available for printing. Recent reports of the application of these printed platformed are highlighted to enable readers appreciate the progress in 3D/4D printing in dentistry.

***Keywords***: *3D printing, dentistry, dental prosthetics*

## Introduction

The science behind the medical and health care industry has witnessed revolutionary trends in the last decades. With the rapidly emerging technological advances, health industry has shifted its paradigm towards providing the best and minimally invasive, novel treatment options to the patients to choose from. 3D technology, after its introduction in medicine and health care, has become an indispensable tool in surgical armamentarium. 3D printing allows to manufacture custom made models, implants, prosthesis and surgical guides that have wide range of applications from patient education to prosthetic rehabilitation. Digitalization of patient data to a printable format allows pre-planning, modifying and simulating the procedure. The success of 3D printing being so popular in the field of medicine and surgery can be attributed to its cost effectiveness and less time consumption over traditional methods.

The first 3D object by 3D printing was printed by Charles Hull in 1983. Traditionally, before the advent of technology in medicine, young surgeons and trainees were trained on animal models, human cadavers and mannequins for hands on experience. This had inherent drawbacks like limited supply, lack of pathology, inconsistent human anatomy and cost of handling and storage. 3D printed learning models served as an excellent alternative as they are economical, can be fabricated in less time, can be sterilized and utilized if the prosthesis has to be implanted later. Also, by multi-material printing it is possible to incorporate different materials in different sections in the same model to represent bones, organs and soft tissue for a better tactile feedback. The 3D printed custom models aid in diagnosis, communicate the surgical steps to colleagues and explain the upcoming surgical procedure to the patient which enables them to interact with the prosthesis or modify the treatment plan accordingly. While 3D printed devices and implants are already popular in medicine and surgery, in the recent years it is slowly evolving in the field of dentistry too, with impressive outcomes.

Digitalization in dentistry has opened doors for innovative treatment options in all the branches of dentistry. It is now possible to manufacture patient specific customized braces, aligners, restorations, castable crowns, denture bases and framework etc. which are otherwise tedious and time consuming procedures, in less time.

**Stereolithography (SLA)**

SLA is the first commercially available technology in 3D printing. This method involves photoinduced polymerization in order to create layered structures, using highly cross-linked polymers [1]. This technology may be subdivided into different categories based on the type of platform motion and laser movement. Nevertheless, the printing procedure involves three major steps: light/laser exposure, platform movement, and resin refilling. A 3D digitized model, which is used 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 (Fig. 1 A and B) [2].

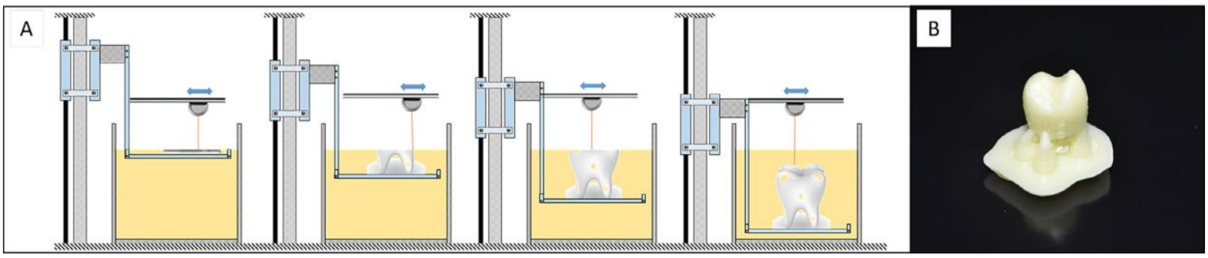


Figure 1. Stereolithography printing. (A) Layer by layer printing process. (B) An example of a crown printed with stereolithography prior to removal of supports and polishing [Sakly A, et al-2014].

The discontinued manner of processing can be overcome by combining SLA with continuous liquid interface production. The latter is a proprietary method of 3D printing that uses photopolymerization to create smooth-sided solid objects [3]. Variables such as light source intensity, scanning speed as well as the amount of resin monomers and photoinitiators can be controlled to achieve the required modelling kinetics and properties of the final product [4].

Currently, SLA is applied in the manufacturing of temporary and permanent crowns and bridges, temporary restorations, surgical guides, templates, and dental model replicas (Fig. 1 B) [5]. Table 1 represents the pros and cons of 3D/4D printing methods in dentistry and maxillofacial surgery.

Stereolithography allows 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 long- term use [6]. However, a certain cytotoxicity of the printed appliances may be caused by the leaching of residual unreacted resin monomers from the printed appliances. The may affect the longevity of the appliances.

**Table 1. Advantages and disadvantages of 3D/4D printing methods in dentistry.**

| 3D/ 4D printing system | Material characteristics | Materials | Advantages | Disadvantages |
|---|---|---|---|---|
| **Stereolithography (SLA)** | Light curable resin | Epoxy and methacrylate monomers | Product resolution - Efficiency - Short working time | - Over-curing - Lack of surface smoothness - Limited mechanical strength - Irritant |
| **Selective laser sintering (SLS)** | Powder | - Polymers - Ceramics - Metals | - Structures are fully self-supporting - Protective gas in not needed - Vast variety of materials can be selected - Little to no thermal stresses are accumulated on the component - Components exhibit excellent mechanical properties - Relatively fast method | - Sample surfaces appear porous and rough - Harmful gases release during fabrication - Materials waste is relatively high - Raw powders are expensive to an extent - Post-processing is often expensive and tedious |
| **Fused deposition modeling (FDM)** | Thermoplastic polymer and composites, low melting temperature metal alloys | Paste - Wire | - Filaments are cheap and arrive in various colors - Easy to change materials - Cost-effective maintenance - Capable of fast 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 - Support structure is required in some cases - 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** | 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 - No need for post-modification - Supporting wide range of materials | - Irritant - High cost |
| **Powder binders** | Materials which are available in powder | Metal - Ceramic - Plastics | Safe material - Short working time - Suitable mechanical performance - Low cost | - Low resolution - Low strength - Cannot be soaked/heat sterilized |
| **3D/ 4D printing system** | **Material characteristics** | **Materials** | **Advantages** | **Disadvantages** |

| | | | | |
|---|---|---|---|---|
| **Digital light projection** | Light curable resin | Resin | - High complexity and excellent surface finish - Short timeframe - Good accuracy - Smooth surfaces | - Limited material selection - Photocurable resin can cause skin sensitization, and maybe irritant by contact |
| **Computed axial lithography** | Light curable resin | Resin containing dissolved oxygen | - It can be used in specific conditions where existing methods fall short, such as: • Printing soft materials that cannot maintain the forces applied during layerwise printing, • Creating lenses with smooth curved surfaces, • Encapsulating other objects in three dimensions | - Limited material selection |

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

Nevertheless, SLA-printed dental devices suffer from poor mechanical properties caused by the limited choice of resins that can be photopolymerized [2]. An interesting option is the nanoparticle incorporation into the polymeric matrix, which can improve the mechanical properties [7]. 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 solve the issue of microbial colonization of oral devices [8]. Overall, SLA is a rapid, convenient and multifunctional technique in 3D dental printing (Fig. 1).

**Digital light projection (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 ascending or descending, as shown in Fig. 3 B [9]. 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 up/down as the thickness of a layer until completing the entire part [10]. A digital micromirror device is used to reflect the light. This device consists of a matrix of microscopic-size mirrors. These mirrors conduct 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 [11].

Even if both SLA and DPL are very similar, there are also some differences between these techniques (Fig.3). The main difference is 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 accurate 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.

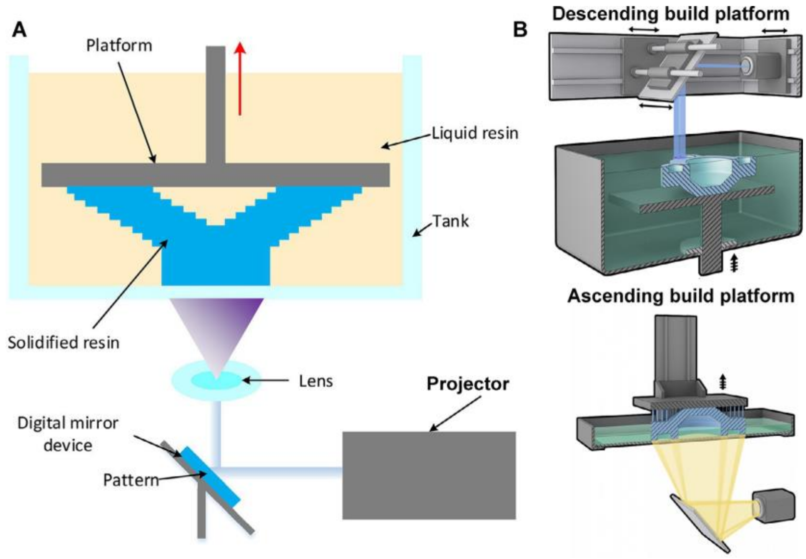


Figure 2. Digital light projection (DLP). (A) Schematic of the printer components and printing procedure. (B) Demonstration of two kinds of platform movements in DLP method [Pan Y-2012] .

In summary, DLP is advantageous in the fast printing of bigger parts with fewer details while SLA is advantageous in printing accurate parts with intricate details **[12]**.

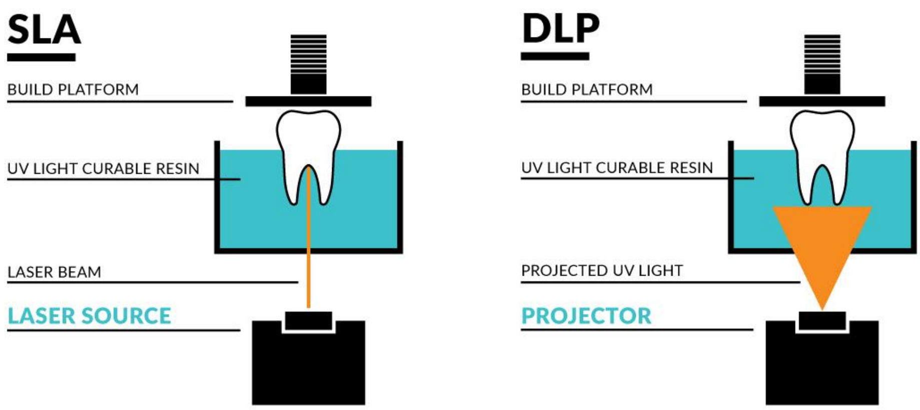


Figure 3. Differences between SLA and DLP

**Fused deposition modelling (FDM)**

FDM, which is also known as fused filament fabrication (FFF), is the trade name for a polymer, composites, or metal alloys softening process; this particular technique resides over 20 years ago. FDM is the second most commonly used 3D printing technique, after SLA [13]. This method is also remarkably cheaper [14].

The basis of this technique is the principle of strand extrusion: the desired type of thermo-plastic materials, shaped as strands, is delivered to the extruder. Upon softening, the heated viscous plastic is deposited by an extrusion head that results in layer-by-layer fabrication of the digitized model (Fig. 4) [15]. Unlike SLA, individual layers within the object have reduced bonding and thus, the final product has greater anisotropy [16]. Thermoplastic polymers and their composites (such as acrylonitrile-butadiene-styrene, polycarbonates and polysulfones) along with low melting temperature metal alloys (e.g., bronze metal filament) are the most common employed FDM filaments [14]. 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) [14].

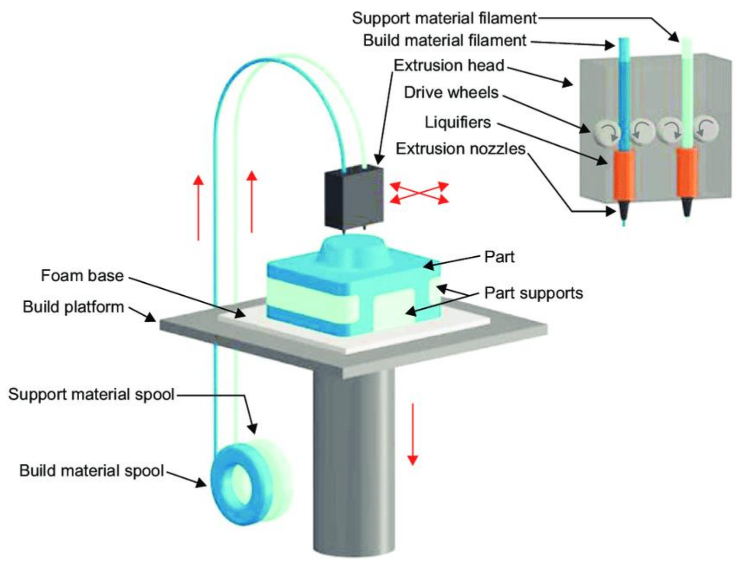


Figure 4. Fused deposition modelling (Heras ES – 2017)

Due to the weak mechanical properties of these un-filled thermoplastics, FDM is used only for the printing of temporary crowns and bridges in dentistry. Similarly to SLA, processing commences with the acquisition of computer-aided design (CAD) images; based on these digitally acquired images, FDM is able to rapidly print the destined product**.** Fused deposition modelling is the technology utilized in most low-cost 'home' 3D printers.

It enables the printing of crude anatomical models without too much complexity. This technique is also used in machines with low maintenance profile and in scientific research [13].

**Selective laser sintering (SLS)**

SLS is a technique where a high energy beam laser is used to induce fusion of the powdered raw material. 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 method does not require additional material support during printing because support is provided by the powder surrounding it [17].

Multi-purpose study models, guides for drilling and cutting as well as metal frameworks can be created using SLS (Fig. 5). The advantages of SLS include the use of autoclavable materials, mechanical functionality of the printed object, reduction in production cost with increase in production volume. The main disadvantages of this printing technique are represented by a certain health risk generated by the inhalation of the powdered raw material, the initial high cost in setting up and the need for supplementary supplies such as compressed air for proper functioning of SLS [18].

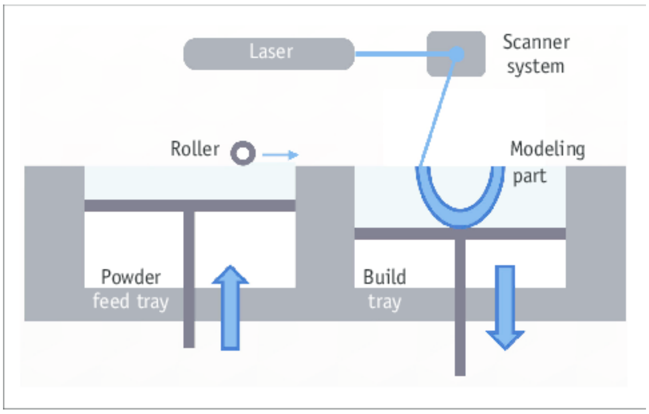

Figure 5. Selective laser sintering principles

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 rests lowers 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 left to cool down after printing is complete [19].

Another benefit of SLS is the almost utilization readiness of the printed object. Whereas other printer methods necessitate a supplementary sanding step or other forms of finishing before the printed products are usable, this step is usually not mandatory for the SLS technique. Because SLS printers do not require structural support during printing, the processing time is considerably faster compared with SLA and FDM [20].

Three types of SLS printing are available: metal-based, ceramic-based, and polymer-based SLS. The metal-based technique utilizes fine metal powders, whereas the polymer-based 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. In addition, SLS technique has been employed for fabricating ceramic parts [21].

Knowing that ceramic powders need an appropriate exposure time to result in the desired density, the target temperature should be lowered to facilitate the densification. An option could be to mix other organic (e.g., polymers) or inorganic (e.g., metal-based low-melting materials and glass) compounds, as binders in the ceramic powder; binders melt in the heated powder bed surface and create a bonding phase around the ceramic particles. Moreover, these binder products are more sturdy to temperature variations. In order to prevent the oxidation of the binder contents, inserting atmospheres is mandatory. Organic contents can be removed in the high-temperature firing in furnace, while the inorganic parts remain [22].

Infiltration/isostatic pressing along with SLS enhances the mechanical performance of the ceramic parts by maximizing the final density [23]. Several challenges in the fabrication of ceramic parts with optimal mechanical performances, such as mechanism of melting and consolidation, powder deposition, the interaction between laser and powder, or thermal and residual stress analysis can occur [24].

**Powder binder printer**

This 3D technique uses liquid adhesive droplets within a modified inkjet head. The inkjet head releases these droplets which infiltrate a layer of powder. This step is repeated layer by layer, until the final product is manufactured.

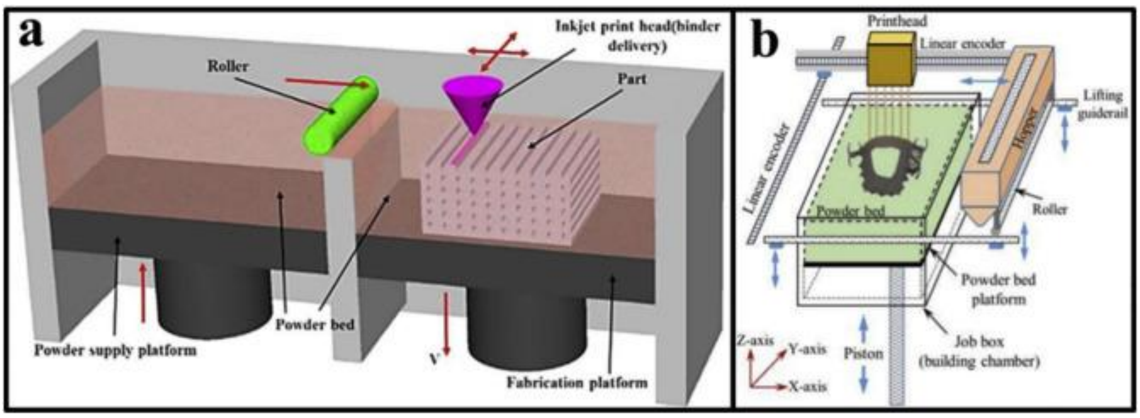


Figure 6. Powder binder printer principles (Mostafaei A-2017)

Study casts and prototypes represent the main application of powder binder printing in dentistry. Importantly, the resulted objects are fragile and inaccurate. The manufacturing process is also messy due to the use of powder (Fig. 6) [25].

**Photopolymer jetting**

This technology involves the combination of two techniques, using a dynamic printing head and photopolymerizable polymer. The light-sensitive polymer is jetted to a building platform from an inkjet-type printing head and cured layer by layer on the descending platform (Fig. 7) [26]. A supporting structure is also printed with fragile support material for easy removal. This technology enables printing of an extensive range of resins and waxes for casting. Silicone-like rubber materials may also be used for printing complex and highly-detailed products with a resolution of ~16 microns. The printed products may be represented by anatomical study models or dental crowns.

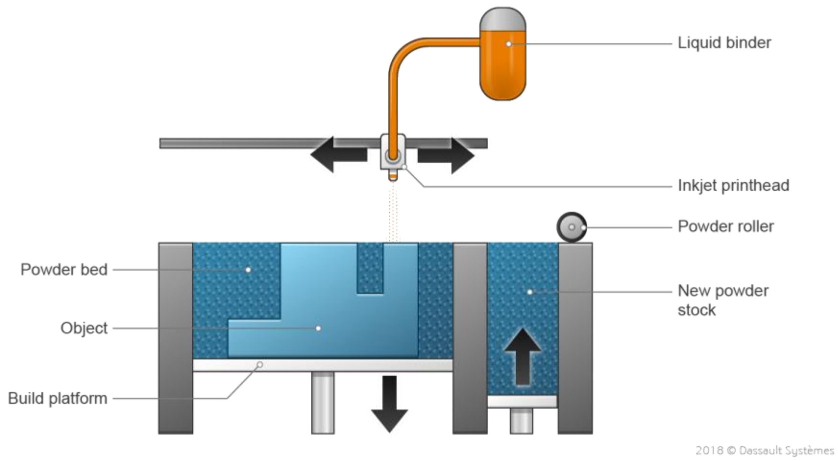


Figure 7. Photopolymer jetting (Lipson H-2013)

In this printing technique that implant drill guides may be printed rapidly and economically with better quality. 3D jet printers utilize multiple printing heads to cover the working platform width [27]. The printing head and working platform move bidirectionally but independently. An ultraviolet light source is used to harden each layer of resin or wax that has been jetted.

The main advantages of this technology are rapid manufacturing, surface smoothness and cost efficacy. The disadvantages include potential skin irritation, the high cost of the material, difficulty in removing the material completely due to rigid support, inability to be heat-sterilized [16].

**Computed axial lithography**

Computed axial lithography is a form of volumetric printing technique. The idea of computed axial lithography is inspired by computed tomography scanners. In computed tomography, X-ray scanning is performed from many different angles. This concept was utilized in the development of computed axial lithography [28]. The object is fabricated by projecting a light (with specific wavelength) containing many 2D pictures (from different angles of the object) to a rotating container of photocurable resin (Fig. 8).

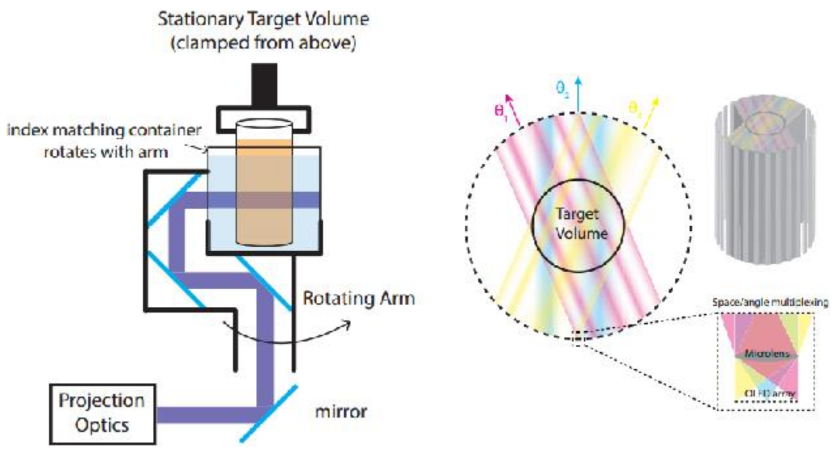

Figure 8. Computed axial lithography

Computed axial lithography has some similarity to DLP method as both systems use projector as light source to photopolymerize the resin. The difference between computed axial lithography and other conventional printing techniques is that light polymerization is applied at several angles to the material, where as other printing methods utilize layer-by-layer polymerization. In other words, computed axial lithography can produce the entire object at once (not layer by layer).

Photopolymerization of the resin material permits manufacturing of products with higher complexity and better surface finish in shorter timeframe, compared with other methods. Centimetre-scaled products may be printed within a minute with the use of computed axial lithography. The products printed with this technique can be easily designed with CAD and saved in stereolithography file format. To date, high viscosity resins or solid materials are used predominantly for this technique. The application of materials with low viscosity may permit printing of tissues in the future. However, more *in vivo* studies are required to investigate the mechanical and chemical properties, tolerability and biocompatibility of the photopolymerized resin products prior to their recommendation for clinical applications [29].

**Conclusions**

There is a great variety in 3D printing technologies. Integration of 3D printing into different aspects of contemporary dentistry has enabled the production of complex prosthodontic, orthodontic and surgical devices that demand flexibility and abrasion resistance from the molding materials. These techniques may vary in quality, simplicity and accuracy and the designated final object will certainly dictate the method of choice.

**References**

1. Fan D, et al. Progressive 3D printing technology and its application in medical materials. Front. Pharmacol. 2020; 11:122.
2. Sakly A, et al. A novel quasicrystal-resin composite for stereolithography. Mater. Des. 2014; 56: 280–285.
3. Tumbleston JR et al. Continuous liquid interface production of 3D objects. Science 2015; 347:1349–1352.
4. Jain R, Supriya BS, Gupta K. Recent trends of 3-D printing in dentistry-a review. Ann. Prosthodont. Rest. Dent. 2016; 2:101–104.
5. Hazeveld A, Huddleston Slater JJR, Ren Y. Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. Am. J. Orthod. Dentofac. Orthop. 2014; 145:108–115.
6. Noorani R. 3D printing: technology, applications, and selection, CRC Press, 2017.
7. Bustillos J, et al. Stereolithography-based 3D printed photosensitive polymer/boron nitride nanoplatelets composites. Polym. Compos. 2019; 40:379–388.
8. França R, et al. 3D printing—additive manufacturing of dental biomaterials. Dent. Biomater. 2018; 2:421.
9. Pan Y, Zhou C, Chen Y. A fast mask projection stereolithography process for fabricating digital models in minutes. J. Manuf. Sci. Eng. 2012; 134: 051011.
10. Ge L, et al. A digital light processing 3D printer for fast and high-precision fabrication of soft pneumatic actuators. Sensors Actuators A Phys. 2018; 273:285–292.
11. Lu Y, et al. A digital micro-mirror device- based system for the microfabrication of complex, spatially patterned tis- sue engineering scaffolds. J. Biomed. Mater. Res. 2006; 77A:396–405.
12. Bagheri Saed A, et al. Functionalized poly l-lactic acid synthesis and optimization of process parameters for 3D printing of porous scaffolds via digital light processing (DLP) method. J. Manuf. Process. 2020; 56:550–561.
13. Jain P, Kuthe AM. Feasibility study of manufacturing using rapid prototyping: FDM approach. Procedia Eng. 2013; 63: 4–11.
14. Cuan-Urquizo E, et al. Characterization of the mechanical properties of FFF structures and materials: A review on the experimental, computational and theoretical approaches. Materials (Basel) 2019; 12: 895.
15. Heras ES, et al. Plate auto-level system for fused deposition modelling (FDM) 3D printers. Rapid Prototyp. J. (2017); 23:401-413.
16. Kessler A, Hickel R, Reymus M. 3D printing in dentistry—state of the art. Oper. Dent. 2020; 45:30–40.
17. Olakanmi EO, Cochrane RF, Dalgarno KW. A review on selective laser sintering/melting (SLS/SLM) of aluminium alloy powders: processing, microstructure, and properties. Prog. Mater. Sci. 2015; 74:401–477.
18. Kruth JP, et al. Digital manufacturing of biocompatible metal frameworks for complex dental prostheses by means of SLS/SLM. Proc. VRAP, Leir. 2005;139–145.
19. Kruth JP, et al. Rapid manufactur- ing of dental prostheses by means of selective laser sintering/melting, Proc. AFPR S. 4 2005;176–186.
20. Okazaki Y, Ishino A. Microstructures and mechanical properties of laser-sintered commercially pure Ti and Ti-6Al-4V alloy for dental applications. Materials (Basel) 2020; 13:609.
21. Lakshminarayan U, Ogrydiziak S, Marcus HL. Selective laser sintering of ceramic materials, 1990 Int. Solid Free. Fabr. Symp., 1990.
22. Chen Z, et al. 3D printing of ceramics: A review. J. Eur. Ceram. Soc. 2019; 39: 661–687.
23. Wohlert M, Bourell D. Rapid prototyping of Mg/SiC composites by a com- bined SLS and pressureless infiltration process, 1996 Int. Solid Free. Fabr. Symp., 1996.
24. Leong SS, et al. Direct selective laser sintering and melting of ceramics: a re- view. Rapid Prototyp. J. 2017; 23: 611–623.
25. Mostafaei A, et al. Binder jet printing of partial denture metal. Mater. Sci. Technol. 2017; 2017:289–291.
26. Lipson H, Kurman M. Fabricated: The new world of 3D printing, John Wiley & Sons, 2013.

27. Mai HN, Lee KB, Lee DH. Fit of interim crowns fabricated using pho- topolymer-jetting 3D printing, J. Prosthet. Dent. 2017; 118:208–215.
28. Kelly BE, et al. Volumetric additive manufacturing via tomographic reconstruction, Science 2019; 363:1075–1079.
29. Yu C, et al. Photopolymerizable biomaterials and light-based 3D printing strategies for biomedical applications. Chem. Rev. 2020; 120:10695-10743.