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GRAYSCALE VAT PHOTOPOLYMERIZATION 3D PRINTING: A NEW FRONTIER IN DIGITAL DENTISTRY

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ABSTRACT

In dentistry, 3D printing has become a game-changing technology that allows for accurate, patient-specific solutions for orthodontic, prosthetic, and restorative applications. Basic concepts of the dental 3D printing are given in this article, with a special emphasis on Vat Photopolymerization (VP), the method that was most frequently used in dental the practice. Stereolithography (SLA), digital light processing (DLP), & liquid crystal display (LCD or mSLA) technologies are all included in VP. These technologies create intricate dental components by layer-by-layer curing photosensitive resins. The new Grayscale Vat Photopolymerization technique, which uses controlled light intensity modulation to achieve varying curing depths inside a single layer, is given particular attention. This technique opens up new possibilities for dental 3D printing by greatly improving mechanical performance, geometric accuracy, and surface smoothness. The paper highlights the effects of conventional and grayscale VP systems on print resolution, material biocompatibility, and overall treatment quality while discussing their benefits, drawbacks, and restrictions. Additionally, important phases of dental 3D printing method are examined, from digital modeling and computer-aided design (CAD) to post-processing procedures like rinsing and post-curing, which are essential for guaranteeing the dependability and safety of patient-specific medical equipment. The research concludes by outlining pertinent legal and regulatory factors that affect the production of customized dental goods. For dentists, researchers, and medical professionals investigating the growing importance of grayscale vat photopolymerization in the advancement of digital dentistry.

Keywords: *Gray Scale Vat photopolymerization, 3D Printing, Dentistry, dental additive production*

INTRODUCTION

In the dentistry industry, additive manufacturing (AM) technologies are not new. In contemporary dentistry, these procedures are also known as "3D printing" also have attracted a lot of interest. Researchers are excited and hopeful about the potential this technology has to give the dentistry industry, raising the standard of dental practice.(1, 2, 3, 4) Directed Energy Deposition, Material Extrusion, Binder Jetting, Powder Bed Fusion, Vat Photopolymerization (VP) and Sheet Lamination are the seven categories into which AM processes fall under the international standard ISO/ASTM

52900:2021 (Additive manufacturing General principles Fundamentals & vocabulary). Different technologies and materials are used in each of the aforementioned procedures. VP covers procedures that cure liquid photopolymer resin in vat layer by layer using UV light. These procedures employ liquid photopolymer resins, which are typically composed of photo initiators, oligomers, and (meth)acrylate monomers. Afterward photo initiators produce free radicals in the presence of a UV light source & monomers & oligomers begin to form bonds via the chain of radical polymerization mechanism, curing takes place.

VPP was the first 3D printing method to be developed(5), and because it can quickly create intricate structures with excellent resolution(6), it is very interesting in the biomedical industry. In summary, VPP employs liquid resin monomers or oligomers that undergo polymerization upon exposure to a certain wavelength of light(7). There are several types of VPP; historically, stereolithography (SLA) was the first to be invented, It cures the resin it comes into touch with by using a UV laser beam that follows predetermined pathway(8). SLA technique also comparatively sluggish since the laser must ultimately move & trace the whole volume of the item being printed pixel by pixel. Instead, a full layer of resin is exposed to the light at a time using mask projection VPP techniques, such as those that use a liquid crystal display (LCD) or a (DLP) digital light projector, hiding the portions that do not require curing(9). Continuous printing at speeds up to a hundred times faster than SLA & DLP is possible using the continuous light interface production (CLIP) approach, which makes use of a more sophisticated projector and an oxygen layer above the vat base that inhibits polymerization (6). Lastly, two-photon polymerization (TPP), which uses two femtosecond laser beams, can be employed if sub-micrometer resolution is needed; however, the sizes of printed items that can be obtained using this technology are presently limited(10). Biocompatibility is a significant obstacle when using VPP to 3D print products for usage in the human body(11). In addition to being printable, a 3D-printed material must meet a number of requirements in order to be biocompatible, such as having suitable mechanical characteristics, harmless degradation byproducts, excellent degradation kinetics, & biomimicry(12). Distinctive photosensitive resins include monomers such as acrylates or methacrylates, together with potentially hazardous photoinitiators and photostabilizers(13). Developing new biocompatible materials for the VPP 3D printing is therefore quite popular. An alternative strategy is to modify materials that already been demonstrated to be biocompatible to the VPP 3D printing method rather than creating entirely novel material chemistries for this determination.

The oldest technological principle, vat photopolymerization (VP) printing(14), has established itself as the standard in dental practice due to its cost-effectiveness, accuracy, repeatability, and adaptability. Despite being utilized by some practitioners to create models, material extrusion (MEX) printing, particularly (FDM), not be discussed here. These technologies are in fact inadequate for the long-period fabrication of the dental medical devices due to the lengthy printing process, higher porosity of the materials formed, and lack of steady biocompatible materials(15). Additionally, it has been demonstrated that this technology yields materials that are less precise than those suggested and reported in this article(16, 17). As of right now, none of the other technologies depicted in Figure 1 are practical. In the upcoming years, the majority of dentists are probably going to have a 3D printer. For the on-demand manufacturing of specific devices, 3D printing is a perfect addition to intraoral scanners due to its lower acquisition cost when compared to subtractive methods.

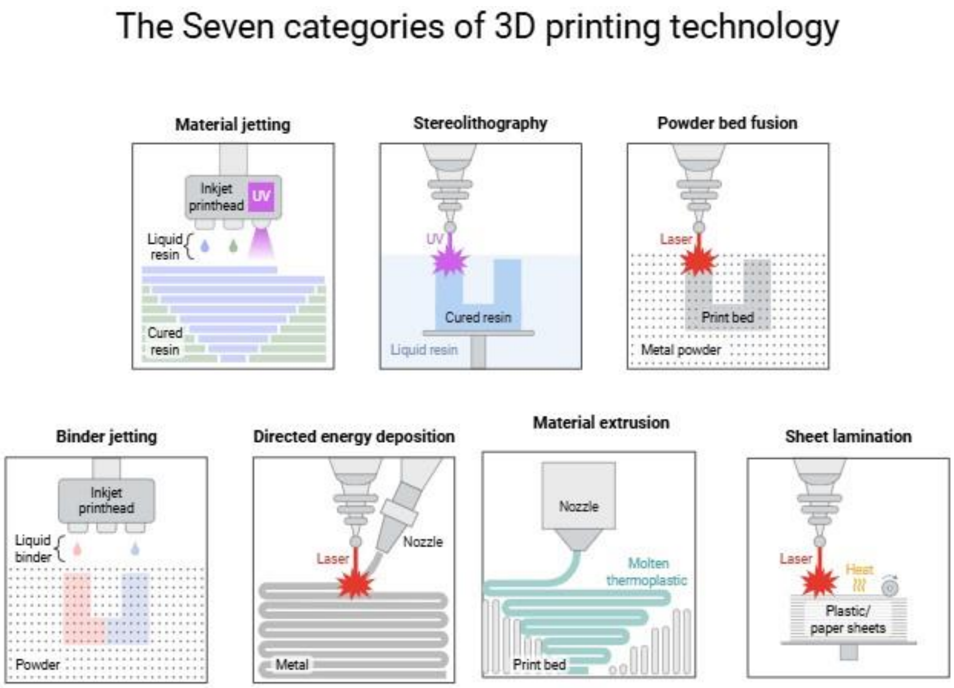

Figure 1: The seven types of 3D printing technology

The advancement of 3D printing technology has opened up two significant avenues for its use in the medical field. On one hand, the ongoing essential for prostheses or substitutes of various body parts in the domains of dentistry, orthopedics, & general or oral & maxillofacial surgery has led to the development of more affordable, quicker, more accurate, and customized replacement ideas that greatly enhance patient consequences & quality of life(18, 19, 20).

2.0 Literature Review

2 Major Approaches for Vat Photopolymerization Printing

VP printing can be achieved through three different technologies (21)straight light projection using an LCD screen & indirect light projection (DLP: digital light processing), & stereolithography (SLA: stereolithography apparatus). Unpolymerized, liquid, thermosetting, and photosensitive resin is kept in a clear bottom vat for every printer. Photopolymerization from the top of the tank is used in other methods. Nevertheless, these technologies will not be discussed here because they are not utilized in the dentistry area(15, 21). To minimize the bond of polymerized parts, improve fluid rheology, withstand heat better, & routinely mixed the resin in the printing vat, also called the printing tank, different brands rely on different technologies. This significant area of study and growth accounts for the high price of these consumables.

The build plate, which is frequently made of metal, is immersed in the vat of photosensitive resin as the printing process starts. The preliminary coating of resin on the construction plate hardens via a photopolymerization process as it gets closer to the clear bottom surface. The polymerization of the monomers into polymer chains is initiated by photoinitiators, which are activated when the resin is visible to particular light wavelengths. The photopolymerization seen in the use of straight composites in dental operations is entirely comparable to the related mechanism. The build plate is then raised a few tens of microns vertically along the Z-axis. This precise value, which relates to the layer thickness, is determined by the user. The successive layers are then formed using the same photopolymerization process until the desired product is produced.(22)

The ability of a printer to replicate a printed device's finest features is known as its resolution(22). The Z-axis represents the width of a each printed layer, and the X, Y, and Z axes are used to define this resolution in µm or DPI (dots per inch). The object's external details are more accurate and the printing time increases with decreasing value(23). Depending on the intended level of complexity and the clinical indication, its thickness usually varies from 25 µm to 200 µm. A layer diluter than the printer's determination cannot be printed. For instance, cumulative the vertical printing resolution from 100 µm to 50 µm will result in twice as many layers and twice as much printing time(15).

2.1 Stereolithography Technique

A high-energy laser is used in this printing method to draw a cross-section of the item and start each layer's photopolymerization reaction (Figure 2)(22). This feature accounts for the generated elements' excellent isotropy and dimensional stability(24).Nevertheless of extent and location of the article on the build plate, polymerization may take place with steady precision at consistent breaks on the X and Y axes thanks to a series of mirrors confidential the laser generator known as Light Power Unit (LPU). The laser generator's diameter and the servo-motor systems' repeatability of positioning have a direct bearing on this resolution. Regardless of the size and location of the object on the build plate, polymerization may happen with constant precision at regular intervals on the X and Y axes thanks to a series of mirrors within the laser generator known as the Light Power Unit (LPU). The diameter of the laser generator and the accuracy of the servo-motor systems' placement are directly correlated with this resolution(21). This method uses a build plate of moderate to substantial size to print numerous objects at once without compromising print quality. As a result, stereolithographic manufacturing produces very exact objects(25). The focusing laser must, however, cover the full surface of a given printing layer; the printing time increases with the size of the item to be produced or the quantity of items to be printed(21).

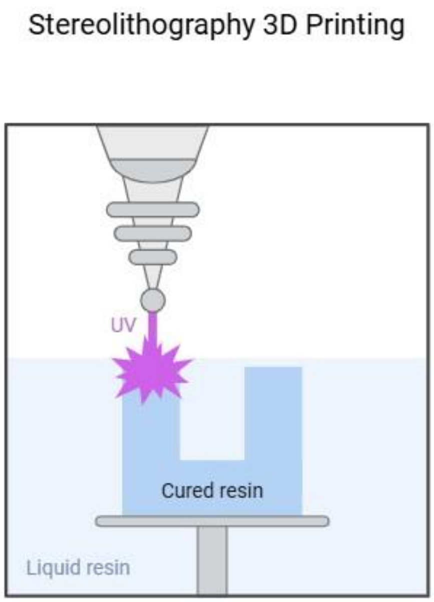

Figure 2: Process of stereolithography printing technology

2.2 Digital Light Processing technique

The American Society for Testing & Materials classifies both DLP AM and SLA technology as AM, which makes them extremely similar. The SLA & DLP differ mostly in the light foundation (Figure 3). DLP makes use of a tiny projector that is positioned far from the resin tank. It is made up of a matrix with over a millions digital micromirror devices (DMDs), each from which has two possible locations: one where it reflects light in the direction of the tank and another where it reflects light outside the tank. This causes the bottom of the tank to display a "pixelated" image(26). The projected image's resolution is correlated with the number of mirrors (27).

Therefore, the printing period for somewhat given coating width of resin is the same nevertheless of the printing surface or quantity of items is printed.(15) Chairside restorations, often known as single-session restorations, are only possible using this technology at a dentist office. Most DLP chips cast-off in dentistry have a determination of 1080p. A larger predictable image will result in a poorer resolution. To put it another way, a greater printing area leads to a wider pixel, which produces a more accurate representation of the layer to be printed(26). Since many procedures and compensating software plans try to lessen this result, this technique is still somewhat theoretical. Since most suggestions demand an correctness of about 100 µm, this method has limited functional influence in dentistry(28). However, compared to SLA technology, this method may produce a less smooth surface finish(29). Furthermore, compared to SLA technologies, the potential printing capacity is typically more constrained due to technological issues.(26)

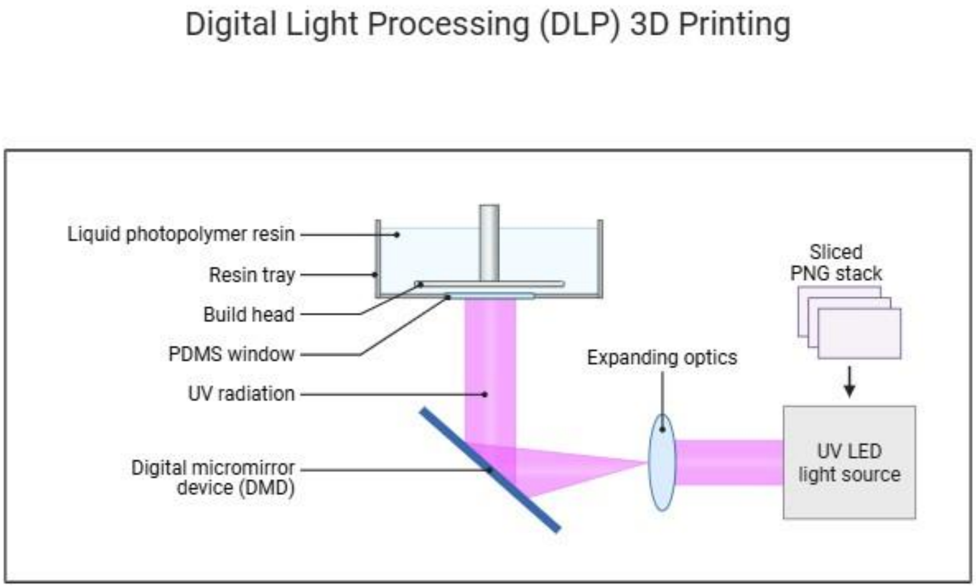

Figure 3: Operation of DLP printing technology

2.3 Liquid Crystal Display technique

Due to the similarities between the two, this technique is sometimes categorized as a DLP technology. But mSLA is much different. An LED projector is concealed overdue an LCD screen next to the printing container in place of DLP chips (Figure 4) (30). The LCD screen filters the monochromatic UV light that the projector releases on the parts of the tank that won't be printed(31). With academic LCD panel purposes ranging from 4 to 12 K, this method allows for higher printing resolutions. As a result of an optical junction event among two adjacent pixels, these values are actually somewhat lower(32). However, the main cause of these printers' limitations is overheating. The LCD screen is significantly heated by the high light strengths needed for layer wise printing, and the cooling that the printer's internal fans offer is insufficient to address this problem. Furthermore, an LCD screen must be treated as a expendable that needs to be swapped after a specific amount of hours of use because it deteriorates far more quickly than an SLA & DLP chip. As a result, the printer's print quality gradually deteriorates until novel LCD screen is installed(33). Because the LCD screen absorbs 90% of the light and only 10% of it may flow through, the intensity of light in LCD AM is comparatively little. Furthermore, as previously mentioned, partial light loss may cause rough revelation of the photosensitive resin at bottom, necessitating routine liquid tank cleaning.

The most popular printers designed specifically for dentistry are Creality Halot (Creality, Shenzhen, China), Anycubic Photon Mono (Anycubic, Kowloon, Hong Kong). The main factor contributing to these printers' current popularity is their cost, which varies by manufacturer and can be two to ten times less than that of a SLA or DLP printer, both of which have similar costs. Lower manufacturing costs [22] and less optimization of nondental-specific LCD printers account for a portion of this pricing disparity. In fact, these printers have few or no authorized printing profiles and are typically less ergonomic.

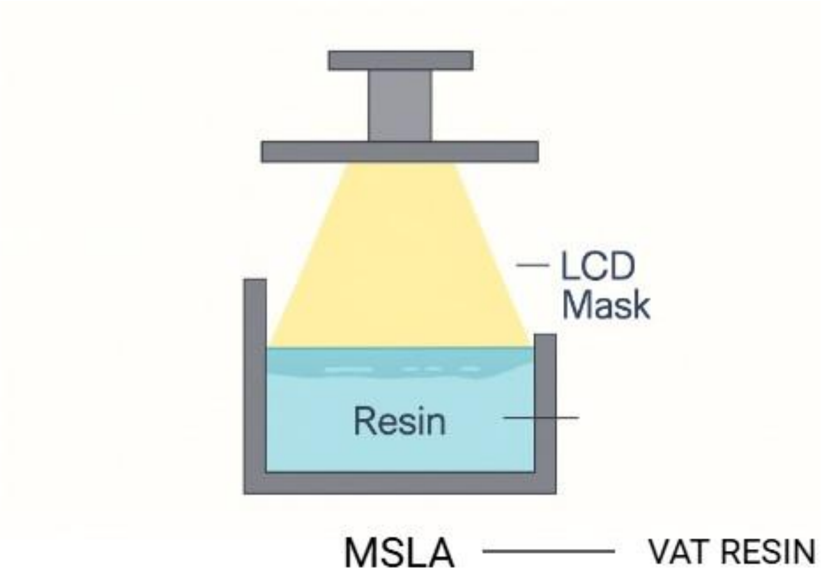

Figure 4: Operation of Masked Stereolithography printing technology

3.0 Pros and Cons of Different 3D Printing Approaches

The specifics of 3D printing techniques are described, along with their advantages and disadvantages. By extending 2D inkjet printing methods, academics at the Massachusetts Institute of Technology (MIT) created the primary 3D printer in 1993(34). Since, a limited more extensively used printing methods have been shaped. These days, are frequent 3D printers used in mutually industry & dentistry thanks to fresh advancements in the development of 3D printing machineries with diverse mechanisms, such as extrusion & sintering. The most popular methods for 3D printing include stereolithography (SLA/SLG), & fused deposition modeling (FDM),or selective laser sintering (SLS), selective laser melting (SLM),& powder binder printers (PBP), & digital light processing (DLP)(35, 36).

In short, the extrusion-based techniques use a computer-controlled jet with a specific width to distribute the chosen material in three directions.

These techniques create a three-dimensional structure at the centimeter scale by continuously ejecting extruded material that is pneumatically or mechanically propelled out of the nozzle(37). Thermoplastic polymers are among the materials that are melted and then forced out of the nozzle in the extrusion-based FDM method. The primary process for creating advantageous 3D structures is the simultaneous deposition of melted material on the instrument support and its cooling(38). Basic and simpler models can be readily built using low-cost extrusion-based processes. The application of microfluidics to the development of the FDM technique has advanced recently. This provides customers with benefits like cheap cost and affordability. The use of microfluidics in the creation of dental prosthesis has garnered a lot of interest(39).

In order to repair or sinter the additional material on three-axis of the moving stage, the laser melting/sintering process uses higher-power pulsated laser light to raise the temperature of particular regions. Numerous thermoplastic materials, counting as glass, ceramics, metals, and thermoplastic polymers, can be fused using the SLS process. The surfaces can then be refreshed using a roller or blade to create new surface layers. Each sintered layer is then coated with a powdered substance. The production of an autoclavable invention that is fingered securely through standard dental procedures is one of the most significant benefits of sintering processes(40). A desktop SLA 3D printer and computer-aided software make it simple to replicate the prostheses in the dental office. At a low point, this boosts manufacturing quality and rate(41).

The liquid resin is preserved layer wise using a projector light foundation in the digital light processing (DLP) method. Each layer is produced upside down. The mixture of DLP and FDM replicas has suggested as a solution to issues with the DLP approach, such as reduction or cumulative the mistake when the scope of the point out differs. FDM inaccuracy for crown prostheses and FDM correctness for full-arched dental replicas have been considered. Therefore, a hybrid approach combining FDM (for the complete dental model) and DLP (for the specific die) is recommended(42).

Using an inkjet head, the device infiltrates colored liquid droplets layer by layer in the powder binder printers (PBP) method(35). But it's crucial to use biocompatible powders in tissue engineering. Because they resemble dental sources, materials based on calcium phosphate will be a good reactive component for implant applications(43).

Finally, photopolymers are used as the printing material in lithography-based processes. The phase changes in various instructions to create the three-dimensional structure while these photopolymers are either nonstop visible to a UV light ray or through a lithography-based ceramic production approach. Motorizing mirrors aid in focusing the light beam on the surfaces that contain the photoreactive liquid resin that is intended to be attached in these methods. Next, a wiper is used to recoat the curved surface. To penetrate or stain the specific regions of the printed material, this procedure is followed by an additional fusing phase(40). These photopolymers have a variety of characteristics, including fracture mechanics and elemental composition microstructure. Three goods' attributes were compared by Ucar et al. The most promising method was the ceramic-based lithography method(44).

Table 1 lists the advantages and disadvantages of the most popular 3D printing methods. The different approaches are also mentioned in Figure 1.

Technique	Advantages	Disadvantages
G-VPP	High Resolution and Precision Reduced Stair-Stepping Effect	High Equipment Cost Complex Calibration
FDM	Inexpensive Because inflammable and non-explosible materials are being used, there is no chance of combustion. The FDM technology permits for the 3D printing of a wide variability of materials. Suitable for building complex structures	Insufficient resolution and precision The printed surfaces frequently require additional processing to smooth or cure them.
DLP	Basic parts of machinery results in a smooth surface.	Surgical guides cannot be printed because of high accuracy issues; smaller pieces and restricted areas have higher permissible resolutions.
SLA	The SLS process can print a wide variety of materials. The preferred method for creating working prototypes and small details with acceptable. Accuracy, precision, and resolution	Costly intricate phases of post-print processing Utilizing biohazardous substances results in a structure that is mechanically weak. The laser component requires costly maintenance.
MJP	Develop models with greater accuracy and precision (trueness) Acceptable ranges for clinical use	Dimensional accuracy requirements
SLS	Low-cost equipment parts The SLS method may print a variety of materials. Ideal for functional prototyping	It is necessary to employ the beginning material in powdered form. Large pieces cannot be precisely manufactured using this method. Potential risks result in high maintenance costs. It can be challenging to print tiny, fine walls (less than 1 mm).

SLM	Cheap components for machinery	Create a state of thermal shock. Elevated melting point

4.0 Advances in 3D Printing and Digital Modeling

Core beam computed tomography (CBCT) & (CAD)/manufacturing (CAM) are two examples of computer-aided technologies that can be used in tandem with three-dimensional printing(45). A computer can reliably simulate teeth in three dimensions thanks to digital oral scanners(46). Furthermore, these scanners can create fixed prostheses without the use of traditional working models(47). The most common materials can now be shaped using a variety of fabrication techniques. 3D modeling can be done using a variety of 3D printing technology, such as stereolithography equipment, SLS, FFF [34, 35], digital light processing, & MJP. As per ISO 5725-1:1994/Cor 1:1998, an precise 3D printing technique possesses both accuracy and trueness simultaneously. In a recent study, three models of dental prosthesis with different resins were designed and manufactured utilizing three dissimilar machineries: SLA, DLP, & MJP. If 3D shade map examination for the MJP reveals surface unevenness at the lowermost level, examination revealed that MJP exhibited significantly superior accuracy and actuality than DLP & SLA approaches(48). CAD/CAM modeling provides two ways to create functional dental models: 3D printing and milling. Dental modeling uses patient data from oral scans as its input. (1) The milling method has additional drawbacks, such as time lost during the fabrication process, excessive cost, and needless missing over milling. (2) Conversely, the 3D printing technique offers greater benefits (e.g., the ability to make many items at once, models of prostheses using less materials, and the potential to fabricate favored prostheses)(49). Software options for CAD/CAM vary (e.g., Slic3R and Geomagic, respectively). The creation of an appropriate CAD solid model is the most crucial stage in the production of the prototype. Hybrid manufacturing (HM), which blends different additive and subtractive fabrication techniques, has received significant attention recently(50). Furthermore, employing CAD/CAM techniques will increase the production yield of prosthesis(51). These methods play a useful function in clinical settings and are commonly used in the construction of dental heads & bridges(52). For instance, Joo et al. published a medical case that used CAD/CAM modeling and 3D printing techniques to fabricate an interim and whole ceramic head for a 45-year-old male(53). Determining the internal and marginal fittings of prostheses, like crowns or bridges, is one of the capabilities of CAD/CAM modeling. Feldspathic ceramic crowns' internal and marginal fit were assessed in a recent study using a CT scan(54). They compared the crown and reference dies' 2D bordering interior fit & 3D volumetric fit measurements. The mean peripheral fit among the three approaches was determined to be 113.2 μm. Clinicians will be able to create better prostheses with the use of these scanning techniques. Abdullah et al. contrasted traditional methods with the CAD/CAM approach in a different study. They looked into how the marginal and internal fit were affected by CAD/CAM methods. They assessed a little gap in temporary crowns. These were made by adding low-viscosity silicone impression material to four types of resin. A mean peripheral gap of 47–193 μm was determined by them(55). Yao et al. also reported a 150–280 μm marginal cleft. They used four different types of resin to create temporary crowns(56).

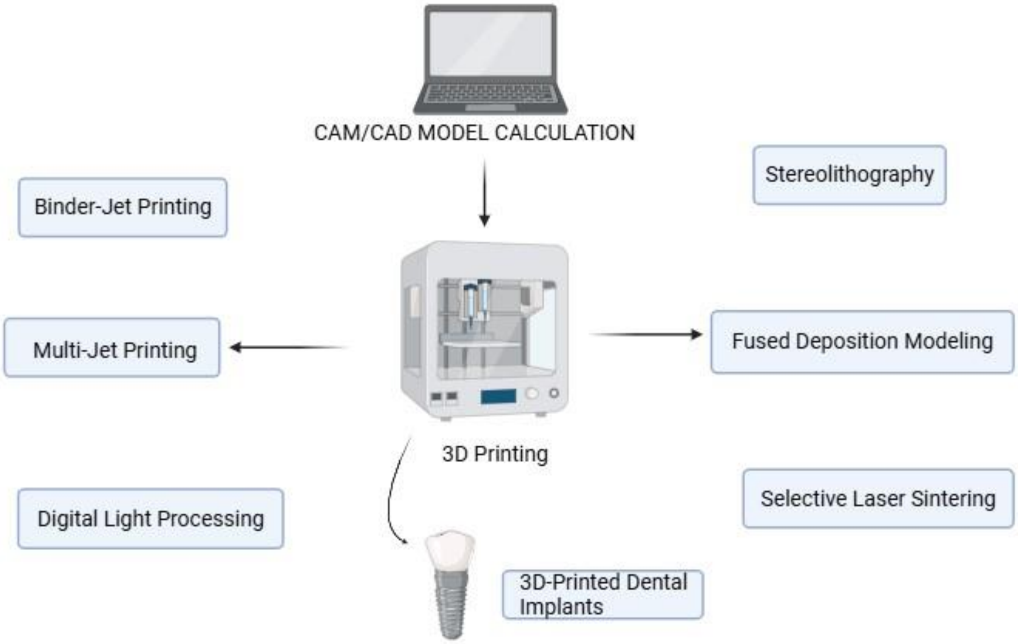

Figure 5: illustrates the six components of the clinical digital process(57).

Surgical guides, aligners, and dental prosthesis are frequently made using a number of software tools(58). Crowns, bridges, & additional dental repairs are frequently intended & crushed using CAD/CAM (computer-aided design & computer-aided manufacturing) software for prostheses. CEREC, 3Shape, and Dental Wings are a few examples of CAD & CAM software used in dentistry(59, 60).To plan and create surgical guidelines that assist surgeons in precisely placing dental implants, specialist software is utilized. X-Guide, Nobel Guide, and Sim plant are a few examples of surgical guide software(61, 62, 63, 64). Software is used to produce 3D replicas of the teeth that can used to make aligners as well as treatment plans. Invisalign, Clear Correct, and Ortho Plan are a few examples of aligner software

5.0 3D Printing Materials in Dental technology

As previously mentioned, a variety of biomaterials, such as hydrogels, ceramics, resins, & thermoplastic polymers, have extensively studied in conjunction with different 3D printing techniques used in dentistry. More precisely, acrylonitrile butadiene styrene (ABS) & polylacticacid (PLA), & other resins are among the materials that are frequently utilized in 3D printing for dental prosthesis. Due to their customizable mechanical and degradational characteristics, a number of synthetic polymers, such as poly (ethylene glycol) (PEG) & poly(vinyl alcohol) (PVA), have used in the 3D printing of dental biomaterials [27,121]. A few more recent materials are created and utilized in dental prostheses 3D printing. Bioceramic is one sample of a novel material that has utilized in the 3D printing of dental prosthesis. Ceramic materials that are biocompatible—that is, safe to use within the human body—are known as bioceramic materials [122]. Because of their strength, longevity, and capacity to adhere to living tissue, they have been employed in a wide range of medical submissions, including dental prosthesis. Bioceramic materials are a suitable option for dental prosthesis that will be exposed to oral fluids and high levels of stress since they are resistant to corrosion and wear. Bioceramic materials such as hydroxyapatite, alumina, and zirconia have utilized in the 3D printing of dental prosthesis [123,124].

For 3D printing of dental prosthesis, composite ingredients—which blend ceramics with additional materials like plastic & metal are excellent choices [125]. These materials are appropriate for a variety of dental applications because they provide enhanced strength, durability, and aesthetics. Furthermore, metal materials like titanium & cobalt-chrome used to make more robust & biocompatible dental prosthesis thanks to some of more recent 3D printing methods like SLS & electron beam melting (EBM). various materials have distinct mechanical qualities, like thickness, in addition to varying fabrication techniques. For instance, three resins bisacrylic, acrylic, & PMMA are employed in a recent study for microcomputed tomography of dental crowns that were 3D printed. Dental crowns made using them and 3D printing technology have thicker films [1

Conclusion

Grayscale Vat Photopolymerization has major benefits over other 3D printing techniques due to its rapid printing speed as well as precision, but its current applications in medicine are limited by the materials used. Adapting existing biomaterials for VPP is a viable method of expanding the available list of compatible materials, though challenges remain. Developing novel resins that reduce toxicity by efficiently removing unreacted monomers would broaden the field's applicability. The ultimate goal of integrating three-dimensional printing into routine dental procedures is still being worked toward. Numerous medical gadgets can be produced using all of the technologies now on the market. The selection of a particular resin, the required printing speed, simplicity of use, and the office's current digital workflow all influence the choice of technology and brand. Although there aren't many restrictions on the laws made for the 3D printing of CMDs, following them and using the precautions recommended here could guarantee the quality of the CMDs that are manufactured.

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