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Current Update on Additively Manufactured Complete Dentures: A Literature Review

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ABSTRACT:

Purpose: The aim of this review was to provide an update on the recent literature on digital denture fabrication with particular emphasis on 3D printed complete dentures in terms of accuracy, fit, mechanical properties, retention, longevity and patients' satisfaction and future directions.

Methods: Two reviewers independently searched the PubMed, Scopus and Google Scholar databases for full-length articles published between 2018 and 2024 that examined digital denture fabrication methods, manufacturing accuracy, clinical outcomes, and physical and mechanical properties.

Results: Regarding manufacturing dimensional accuracy, 3D-printed prostheses were inferior to CAD/CAM milling. 3D-printed prostheses longevity could be questionable due to their poor mechanical properties, surface characteristics and dimensional stability. Patient satisfaction was also lower for 3D-printed denture wearers due to their easy discoloration and opaque monotone shades.

Conclusions: In conclusion, although 3D printing offers promising advancements in efficiency and customization, there are still critical issues regarding the overall quality and performance of prostheses. Ongoing research is essential to address these challenges, improve material properties, and enhance patient outcomes.

Clinical Relevance: This review underscores the importance for clinicians to understand the properties of 3D-printed complete dentures to ensure informed decision-making that optimizes patient care and satisfaction.

1. Background

Although conventional complete denture (CD) manufacturing methods have served the profession well over the years, the recent advancements in computer-aided design and manufacturing (CAD/CAM) have revolutionized conventional practices. Among these innovations, additive manufacturing (AM), commonly known as 3D printing, has transformed the fabrication of dental prosthesis, particularly complete dentures.

The conventional CD manufacturing methods necessitate time-consuming laboratory procedures and up to five patient visits. Moreover, polymerization shrinkage and inadequate fit remain major concerns [1]. In contrast, AM offers an simplified approach that could enhance precision, reduce fabrication time, and allow a new prosthesis to be fabricated rapidly in case of prosthesis loss or fracture due to the advantage of the design storage [2].

While initial studies have demonstrated the feasibility of using AM techniques in denture production, findings regarding their mechanical properties, aesthetic outcomes, and long-term performance remain varied. Some research suggests that 3D-printed dentures may struggle with certain aspects, such as dimensional stability and surface finish, when compared to those fabricated using milling and conventional methods [3,4]. Conversely, other studies highlight advantages in terms of patient satisfaction and comfort [5,6]. This inconsistency in results points to a critical gap in the

literature, indicating that while some benefits of AM are recognized, a comprehensive understanding of its overall effectiveness is still lacking.

These technologies are becoming increasingly popular in clinical settings. Therefore, this review aims to summarize the current literature on CAD/CAM dentures in terms of their clinical outcomes, physical and mechanical properties, their impact on patient satisfaction and their future potential to understand how this technology can impact our patients.

2. Methods

Two reviewers independently searched the PubMed, Scopus and Google Scholar databases for full-length articles published between 2018 and 2024 that examined digital denture fabrication methods, manufacturing accuracy, clinical outcomes, and physical and mechanical properties. The search included not only clinical studies, but also laboratory studies, previous reviews, and systematic reviews with meta-analysis. Search terms used included (additive manufacturing, 3D printing, complete denture, digital denture, CAD CAM denture, stereolithography, direct light processing, jetting, accuracy, dimensional stability, retention, fit, adaptation, printing angle, color stability, biocompatibility, wettability, hydrophilicity, patient satisfaction, esthetics, monolithic denture, tooth movement, patient satisfaction, permanent resin, and nanofilled resin).

3. Discussion

One of the first attempts to shift from conventional manufacturing was made in 1994 by Maeda et al who developed the first computer-aided system for designing and manufacturing removable CDs using 3D laser scanning [7]. In 2010, AvaDent™ and DENTCA™ commercially introduced two visits CAD/CAM dentures. Initially, AvaDent™ introduced a socketed denture base (DB) milled from acrylic resin with prefabricated denture teeth bonded to it, whereas DENTCA™ used 3D printing to fabricate the trial denture, and then the definitive denture was processed conventionally in 3D printed flasks.

In 2015, AvaDent™ announced the fully milled denture at the International Dental Show, where the DB and teeth were milled separately and then bonded together. In the same year, DENTCA™ received Food and Drug Administration (FDA) approval for the world's first biocompatible denture 3D printing resin materials [8].

The three main stages of CAD/CAM technology are data acquisition (image scanning), data processing (CAD), and prosthesis manufacturing (CAM). Manufacturing is done through either a subtractive process, also known as computerized numeric control (CNC) milling, or additive manufacturing, commonly known as 3D printing [9].

SUBTRACTIVE MANUFACTURING

Machining and milling, commonly known as subtractive manufacturing (SM), is a process that uses a controlled material removal method to cut a block of raw material into the desired end shape [6].

Since CAD/CAM dentures are produced from the milling of prepolymerized blocks of acrylic resin, the polymerization shrinkage of the conventional technique is eliminated, while DB adaptation and retention are improved [12].

Milled dentures from standardized pre-polymerized PMMA pucks guarantee the fabrication of homogenous objects with excellent biomaterial properties. The results indicate a better base adaptation, a higher flexural strength, improved resistance to denture staining, and no polymerization distortion while milling. Furthermore, a sophisticated milling strategy facilitates obtaining a detailed and accurate intaglio and cameo surface [13].

The precision of milling is directly related to the milling unit's number of milling machine axes and the diameter of the smallest milling bur. A 5-axis milling machine is used to perform milling on PMMA blanks with a standard diameter of 98.5mm. Although the composition of CAD/CAM PMMA is comparable to that of traditional heat-cured PMMA, CAD/CAM PMMA exceeds conventional heat-cured PMMA in many properties, including surface hardness, flexural strength, flexural modulus, and impact strength. [14] Both materials are biocompatible and have no significant differences in monomer leaching [15].

Interestingly, fungal Candida albicans adherence was significantly reduced in CAD/CAM dentures, resulting in improved hydrophobicity and surface properties. As a result, CAD/CAM dentures may benefit patients who are prone to denture stomatitis [16].

Nonetheless, subtractive manufacturing has drawbacks. A CAD/CAM system may have a higher initial cost than conventional dental equipment [11]. Machining and milling are wasteful processes that remove more material than is used in the final product [17]. Hence, the accuracy of the milling technique is determined by the diameter of the smallest bur; any surface detail smaller than the diameter of the smallest milling bur will be over-milled [18]. The capabilities of the software and digital scanners available limit the potential applications of CAD/CAM [8].

ADDITIVE MANUFACTURING

Additive manufacturing (AM), commonly referred to as 3D printing or rapid prototyping is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer until the desired shape is achieved. AM has many applications in dentistry, including the fabrication of dental models, surgical guides, occlusal devices, dental implants, metal frameworks, complete and partial dentures, and many applications in tissue engineering [19] .

In contrast to subtractive manufacturing techniques, a wide range of raw materials can be employed for object fabrication owing to the diversity of methods used using additive and laying principles. In general, the additive approach is preferred because it generates less waste and does not require the use of burs, leading to reduced costs and higher productivity. Moreover, AM allows for the production of complex geometries and saves time by printing multiple items simultaneously [20].

Furthermore, 3D printing resins demonstrated greater flexural strength and hydrophobicity than conventionally processed PMMA resins [21]. In another investigation, however, poorer flexural strengths were reported as compared to CNC machining, but within clinically acceptable limits [22].

Several fabrication factors can influence the accuracy of printed objects, including polymerization light intensity, print angle, printing layers number and thickness, number of supporting structures, and post-processing methods.

ADDITIVE MANUFACTURING TECHNIQUES FOR COMPLETE DENTURE

Initially, 3D printing was primarily used for making trial dentures, but advancements in materials and technology now enable the production of final CDs that deliver results similar to those of milled dentures [23]. Several techniques can be used in additive technology. The primary difference between these techniques is in the materials used and the manner in which the z-plane, which represents the vertical component of the restorations, was developed to create the 3D object [24].

1. Stereolithography (SLA)

Charles Hull invented the SLA fabrication technique in 1984, and 3D Systems made it commercially available in 1986[25]. SLA is a light-sensitive photochemical reaction in which a focused ultraviolet (UV) light beam or laser beam cures photosensitive liquid polymer layer by layer according to the CAD design. The laser traces each layer on the surface of the liquid resin, at which point a 'build platform' descends and another layer of resin is wiped over the surface, and the process is repeated.

SLA is more expensive than other AM processes, but it provides great precision, a smooth surface finish, and fine details [8]. SLA is more accurate than other 3D printing techniques, and it can create complex geometries with precise details. It is regarded as the gold standard in 3D printing, with resolutions of up to 0.025 mm [26].

2. Digital Light Projection (DLP)

DLP is similar to SLA in that the object is built upside down on a progressively rising platform; however, DLP employs a projector light source that illuminates the whole surface of the photopolymer resin liquid. In comparison to SLA, this results in lower operating expenses and faster processing. Furthermore, it is possible to print multiple objects at the same time with no effect on the printing time [27].

When comparing SLA and DLP methods on printed DBs accuracy, SLA showed higher trueness than DLP. However, both approaches displayed roughly the same precision. Additionally, the optical 3D metrology found that the SLA-printed bases had less staircase effect than the DLP [27,28]. The sagging of the DBs under their own weight during fabrication could explain the lower accuracy of the DLP method [3].

Reportedly, objects produced using SLA technology demonstrated superior mechanical strength in comparison to objects printed with DLP [29].

3. Digital Light Synthesis (DLS)

The DLS technique formerly known as continuous liquid interface production (CLIP), is a recent variation of the DLP technique. In contrast to the layer-by layer printing, DLS combines UVL and oxygen to continually build objects from a pool of resin resulting in faster printing and isotropic mechanical properties [30,31].

Polymerization on the surface near the UV source is prevented by means of an oxygen-permeable window. By removing rate-limiting separation and realignment steps, resin can then freely flow into this liquid "dead zone" at the window surface, enabling continuous production of the part and enabling faster production times. This process creates high-resolution structures that would otherwise be damaged during traditional mechanical separation step of the vat photopolymerization [32].

However, CLIP technology has potential disadvantages. The filled resins can cause uncontrolled light scattering from particles in the dead zone, reducing the strength of laser light reaching the resin and potentially affecting print quality. In addition, resins have different affinities for oxygen, resulting in dead zones of different thicknesses. Therefore, the width of the dead zone and the oxygen penetration rate should be considered in the printing parameters [24].

4. Polyjet 3D printing

Polyjet (PJ), also called multijet printing. is a 3D printing method that allows multiple colors and materials to be printed in a single print.[19]. PJ 3D printer system utilizes different nozzles for dispensing little droplets of varied materials and colors simultaneously then curing them together instantly with UV light. Drops of photopolymer are deposited on a surface and then cured with UV light. Liquid-based photopolymer materials are applied solely to the desired area in each layer and cured with the previous layers by UV light.

This method the printed object is fully encapsulated in support sprues, which can be dissolved using water [3,4]. The absence of fixed support structures present in the DLP method eliminates the sagging of the printed objects under their weight and eliminates the deformation resulting from their removal, which results in higher dimensional accuracy [3].

PJ printing demonstrated higher accuracy and flexural strength when compared to other 3D printing methods [3]. Tasaka et al. reported that maxillary denture bases manufactured using PJ technology demonstrated higher accuracy than those produced conventionally. However, one drawback of this study is the use of non-biocompatible 3D printing resin [33].

5. Fused Deposition Modeling (FDM)

It is a technique for constructing an object by laying a wire of thermoplastic material onto a building platform using a heated nozzle. This method was developed in the early 1990s. The 3D object is created layer by layer from the bottom up until the final shape is achieved. The CAM software controls the nozzle movement, which can be done in both horizontal and vertical directions. The thermoplastic material is partially melted in the nozzle and hardens instantly upon deposition on the building base within 0.1 second [34].

One advantage of FDM is that no post-processing is required. The main limitations of this approach are its limited resolution, moderate speed, and poor surface quality. FDM accuracy is lower than that of other 3D printing processes, such as SLA. The accuracy of FDM depends on factors such as deposition speed, material flow rate, nozzle thickness, and layer height [34].

FDM is limited to thermoplastic materials for complex shapes and geometries. FDM is ideal for dental applications such as customized trays, surgical guides, and wax models of dental prosthesis for casting or polymerization [35]. Recently, FDM technology has been implemented to fabricate thermoplastic partial dentures from pink colored polyamide nylon filaments with sufficient accuracy and in a short time [36].

MONOLITHIC DENTURES

The first step in creating digital dentures involves milling or printing the DB and then attaching prefabricated, milled, or 3D-printed denture teeth using a bonding agent to achieve both pink and white esthetics. These digital manufacturing techniques eliminate the adherence of the

denture teeth to the denture base resin during the heat polymerization stage to form the optimal bond with an interwoven polymer network. Hence, teeth debonding could occur in CAD/CAM digital dentures [37].

The superior bond strength in conventional manufacturing compared to prepolymerized CAD/CAM materials could be explained by the presence of 2.5 times more free monomers during processing [38]. Cohesive failure in the teeth was prevalent in conventional machining, suggesting that there may be higher bond strength between the teeth and the resin base. Whereas 3D printed teeth showed mixed fracture mode. However, both manufacturing techniques exhibit satisfactory bond strength [38,39]. The bonding strength of 3D-printed denture materials varies between manufacturers. For instance, the Ivoclar Ivotion Bonding system achieved the highest bond strength between the printed DB and the teeth manufactured by Formlabs [40].

The manual bonding of individual carded denture teeth into a milled or printed DB may result in undesired tooth movement and deviations from the intended tooth arrangement occlusal scheme, increase the vertical dimension of occlusion, and increase the chairside time for occlusal correction [41].

To eliminate the need for manual teeth bonding to the DB and teeth movement, manufacturers introduced the concept of monolithic dentures. Monolithic dentures are produced as a single piece using either subtractive milling or 3D printing.

The denture base and teeth are exported as one STL file and milled from a single, bi-color disc (Ivotion, Ivoclar Vivadent, Schaan, Liechtenstein). The virtual disc is aligned based on Shell Geometry Technology, a data-based, 3D dental arch structure that defines the transition between the disk's teeth and base areas, resulting in a stress-free, high-strength, homogeneous transition. Therefore, the material exhibits homogeneous strength throughout the disk. This technology offers CAD design strategies for a wide range of jaw shapes and sizes, except in rare cases of very large dental arches [12,42].

Additive manufacturing can also be used to produce monolithic dentures. Initially, dentures are 3D printed in tooth-color resin. Denture characterization is achieved by applying pink composite and stains on the flange to replicate the tissues in addition to a light-cure sealant coat [43]. However, printed monolithic CDs are limited to trial dentures at this time due to the strength, abrasion resistance, and aesthetics of the printing resins [44].

Goodacre et al. compared conventionally constructed dentures (pack and press, fluid resin, and injection) with CAD/CAM (two pieces and monolithic). They concluded that no single technique was able to eliminate tooth movement. The CAD/CAM monolithic denture, however, produced the least tooth movement. Further investigation revealed that posterior teeth move more than anterior teeth [45].

Additively Manufactured Monolithic Dentures Using Material Jetting Technology

Stratasys offered the first jetted monolithic dentures solution on the market with its TrueDent™ resins. DentaJet J5 industrial printer is one of few on the market that can print five materials simultaneously, allowing broad color customization for natural-looking DBs and mimicking the translucency of tooth structure [4].

In September 2024, 3D Systems announced the FDA approval on their jetted monolithic denture solution (NextDent® Jet Denture Teeth and NextDent® Jet Denture Base).

There is not enough evidence in the literature to support this recent technology for CDs. A multicenter study found no significant difference in accuracy between jetted 3D printed trial dentures and milled trial dentures [20]. An in vitro study compared the bond strength between prefabricated teeth attached to a heat-cured DB compared to PJ 3D printing. The study limitation was using a resin indicated for highly realistic model and not for intraoral device [46].

In another study, TrueDent resin was reported to have the highest flexural strength (82.39 MPa), slightly less staining than traditional materials, and significantly lower fracture toughness when compared to Dentca's 3D printed Denture Base II material, milled and conventional heat-cure resins. In addition, it was significantly less translucent than the other groups [4].

CLINICAL OUTCOMES

A. Accuracy and Fit

Previous studies agreed on a clinically applicable error range in 3D printed bases of less than 100 µm [47]. It is

worth noting that dimensional changes continue over time, even after 3D printing and the post-curing process [48]. Hence, if a 3D-printed model is used to construct prostheses, it is advised to be used soon after and for no more than 3-4 weeks [47]. However, the DBs are thinner, and hence, have less shrinkage and more distortion, compared to a model, the dimensional change after 28 days exceeded the minimum value of 100 µm and the maximum value of 200 µm [47].

Moreover, 3D-printed mandibular DBs undergo more dimensional changes in the post-curing process than the maxillary DBs. This can be explained by the palatal part serving as a cross-arch stabilizer, making it more resistant to deformation and experiencing less shrinkage during the post-curing process compared to the mandibular DB [47–49].

FACTORS AFFECTING PRINTING ACCURACY

Printing parameters such as laser intensity and speed, printer and software calibration, resin properties, printing direction and angle, layer thickness and numbers, bond between layers, number of supporting structures, and post-polymerization procedures all influence the final product's accuracy [13]. With the exception of layer thickness and printing angle, the printing parameters are typically set by the manufacturer and cannot be changed [50].

(i) Objects Position on The Build Platform

Arnold et al. discovered that the arrangement of objects on the build platform of SLA printers affects accuracy. They found that the most accurate models are produced in the front area of the platform [51]. In contrast, other studies demonstrated that the objects placed in the center of the build platform are more accurate than those placed at its borders [52,53].

On the other hand, Sherman et al. concluded that all areas of the build plate are capable of producing clinically acceptable models, with solid and hollow model shells, using a DLP printer [54]. More research into how the placement on the platform areas affects accuracy is required.

(ii) Printing Angle

The print angle was found to have an influence on the accuracy of the printed object, which needs to be considered when trying to improve print efficiency (Optimizing printing time and packing density to maximize efficiency on the build plate) [55].

A study evaluated the 3D accuracy of SLA 3D printed maxillary dentures using three different printing directions (0º, 45º, and 90º). Dentures printed at 45º showed the best fit, followed by those printed at 90º, then those printed at 0º [56]. When DLP was utilized to manufacture the CD bases, the printing angle affected manufacturing accuracy, printing time, and material consumption [57].

Yoshidome et al. in 2021 concluded that 45° was the best support angle for fitting accuracy. They explained their findings as the starting points of the build were altered by changing the build angle. Support structures designed at an angle of 0 °, together with the irregular shape of the CD base, resulted in multiple printing starting points. In contrast, there was fewer building starting points for CD bases with a 45° angle [27]. This is consistent with other studies that concluded that the most accurate 3D-printed denture was produced at a 45° build angle [26,52,53,56].

On the contrary, a study on printed DB accuracy concluded that for both SLA and DLP approaches, the 90° orientation resulted in fewer deviations [28]. Jin et al. found no statistically significant difference in the overall tissue surface adaptation of DLP printed bases made with various build angles (90º, 100º, 135º, and 150º) in the maxillary or mandibular arch [58]. Therefore, no consensus could be found in the literature on the optimal printing angle to achieve accurate printing.

Printing build direction does not only affect the object accuracy but also affects mechanical properties. Intraoral devices are subjected to a variety of stresses in the oral environment, the most common of which being vertical occlusal forces. The layer-by-layer nature of AM may affect the strength of printed items through the relationship between the printing layer direction to the direction of the applied load [59].

At 0° print angle, the applied load is perpendicular to the printing layer direction, and at the 45° orientation, the printing layers are in an oblique direction instead of parallel at 90° and this is might increase the strength of the printed object [34,59].

Conversely, other research revealed that layers oriented parallel to the load direction or at a 45° angle to it would

be more able to withstand an axial load than layers oriented perpendicularly. It was explained by similarities in the strength of the bonds between various layers and the bounds that make up each individual layer [53]. Moreover, printing angle may influence the surface roughness and bacterial response [55,60].

(iii) Printing Layer Thickness

The accuracy of additive technology depends on layer thickness and curing beam width. Generally, the thinner the layers and the narrower the curing beam, the more accurate the final product will be. On the other hand, increasing the number of layers and decreasing the diameter of the beam exponentially increases fabrication time. Moreover, as the layer thickness decreases, the strength of the 3D-printed object improves due to better resin curing and less dimensional changes [57]. A minimum printing layer thickness of 25µm has been reported for SLA technology, while inkjet printing can achieve 12µm. However, FDM has an accuracy of around 127µm [56].

Literature regarding the effect of printing layer thickness on DB accuracy is sparse. However, most literature reports printing DBs with layer thicknesses varying from 20 to 150 µm [58,60,61], while other studies did not report this parameter [33,62]. Other studies investigated whether varying layer thicknesses affect DB accuracy and found that the intaglio surface of maxillary trial DBs printed with a 100 µm layer was more accurate than those printed with 50 µm layers [61,63].

(iv) Support Configuration and Position

Printing objects directly on the building platform without supporting structures might increase total thickness, especially in thin areas, and cause compression and protrusion of the initial layer closest to the build platform due to additional laser exposure, thus it should be avoided [26]. While printing without supporting structures necessitates a careless object removal from the build platform which may compromise production accuracy along the Z-axis, as damage to the initial layer is often unavoidable [53].

Studies on 3D accuracy showed a positive deviation, suggesting that there is a space between the experimental and master data in areas of the DB with more support structures. When an area has a high density of support structures, it shrinks towards the support structures as it is more impacted by ultraviolet radiation than areas with thinner support structures [56,64].

(v) Post-processing Procedures

Post-processing of objects generated by SLA and DLP 3D printers is challenging. Post-polymerization duration, temperature, and rinsing solutions can all affect the accuracy of a printed object. The phases of post-processing can be broken down into four categories: removal or demounting, trimming of supporting structures, cleaning, and post-polymerization. Removal refers to physically removing the device from the building platform, cleaning refers to removing uncured resin from the surface of the object by immersing it in an organic solvent such as isopropyl or isopropanol alcohol, post-polymerization is done to achieve complete polymerization of the device using a UV-polymerization machine, and removal of supporting structures with a cutting instrument [32].

Dimensional accuracy was found to be significantly affected by the removal of support structures in the DLP printed objects. That is most likely due to mechanical or thermal stress during removal. Recognizing this conclusion signals that 3D printing techniques with minimum or no support structures possess an inherent advantage [3]. A study concluded that the dimensional changes increase gradually with the increase in the post curing time. Post-curing before support structure removal resulted in significantly higher accuracy than when the support structure was removed [49].

Insufficient post-curing time can lead to dimensional changes or reduced strength due to unpolymerized resin, resulting in fit issues and accuracy errors in artificial tooth attachment due to the joint distortion, leading to an overall occlusal error [49].

B. Retention

Denture retention stands for the resistance in the movement of a denture away from its foundational tissues, especially in a vertical direction. It is the quality of a denture that holds it to the tissue foundation [65]. Retention is key in CD success, and it depends on the patient's anatomic features and appropriate marginal extension and accurate tissue surface fit.

As previously stated, CAD/CAM dentures manufactured using the milling technique demonstrated improved

retention due to the use of pre-polymerized blocks of acrylic resin, elimination of polymerization shrinkage in the conventional technique, and improved DB adaptation [12]. Additionally, several studies have shown that both milled and 3D-printed DBs had significantly higher retention compared to traditional heat-polymerized DBs [6,23,33].

On the other hand, other studies found no clinically significant difference in fit or adjustment was found between digitally manufactured CDs and those of conventional CDs [66]. Acceptable retention values was achievable for milled and 3D printed DBs when using a conventional two-step final impression instead of intraoral scan [2,66,67]. The muco-compressive nature of conventional impression might explain the intimate tissue contact and increased retention in contrast to the mucostatic intraoral scan [67,68].

Nonetheless, the several attempts were proposed to fabricate a CD with functional borders using the intraoral scanner in a fully digital, cast-free workflow. Unkovskiy et al. proposed a “Digital Reline” technique that uses facial scans for aesthetic adjustment and an intraoral scan for initial data acquisition to print a set of trial dentures. Relined with silicone impression material and then scanned extraorally with an intraoral scanner. The best-fit protocol is used to virtually align the relined surface of the trial denture to the existing denture design, hence the name “Digital Reline” [69].

Another proposed technique is to use the existing CD to capture the final impression using a closed-mouth technique. Then the centric relationship is scanned intraorally, and the impression, intaglio and cameo surfaces of the prosthesis are scanned extraorally with an intraoral scanner. A virtual working model is then created by reversing the digital impressions of the intaglio surface in the correct relationship between the jaws [70].

Hydrophilicity has long been known to play a role in increasing denture retention. Water diffuses better on a base surface with good hydrophilicity, which contributes to better retention of the denture Therefore, the wettability of CAD/CAM PMMA may position it as the material of choice to improve the retention of CD fabricated for patients with salivary dysfunction [48].

The intimate adaptation and close fit of CDs' intaglio surfaces to the basal tissues is critical for denture stability and retention. PMMA-milled DBs showed better adaptation than 3D-printed, or wax-milled and conventionally manufactured DBs [9]. Milled CD bases had higher fitting accuracy and trueness when compared to the conventional bases and 3D-printed. Additionally, SLA surpassed DLP in terms of fitting accuracy [27]. However, a systematic review found no clinically significant difference in fit or adaptation between the milled or 3D-printed CDs compared with conventional CDs [66].

C. Patients’ Perception

Several authors found that patients are overall more satisfied with digital denture therapy compared to conventional dentures. The improved satisfaction was attributed to the improved fit and retention and the reduced number of appointments required for denture fabrication [1,2,71].

On the contrary, conventional dentures gained higher patient satisfaction in other studies. In a randomized crossover clinical trial, patients generally expressed greater satisfaction with their conventional dentures compared to the 3D-printed ones, despite the conventional dentures requiring more visits to fabricate [72]. The authors suggested that the improved stability of the conventional dentures might be due to the proper extension of the flanges and good peripheral sealing when using conventional impression technique with functional border molding in contrast to the final impression of the printed denture, which was recorded using prefabricated trays [72].

They also noted that the thinner palate of conventional dentures may contribute to better speech satisfaction. Additionally, patients found it easier to clean conventional dentures and noticed they were less likely to become stained. The authors also highlighted that using multi-layered teeth in conventional dentures, as opposed to single-shaded printed teeth, led to better esthetic results [72].

On the other hand, patient’s perceptions and satisfaction were found to be independent of the manufacturing technique digital and conventional [6]. A systematic review concluded that patient satisfaction and oral health-related quality of life are comparable between conventional and digital manufacturing [68].

The limited esthetic appeal of CAD/CAM dentures remains a concern. Common patients' complaints included shifted dental midlines, excessive gingival display, and unsatisfactory denture tooth and denture base shade [68]. Based on a systematic review, conventional dentures were the preferred choice among clinicians in terms of esthetics [73]. Nevertheless, the esthetics of CAD/CAM dentures will probably undergo rapid evolution, driven by continuously improving technology.

FACTORS AFFECTING DIGITAL DENTURES LONG-TERM BEHAVIOR

Mechanical Properties

Denture teeth strength and occlusal wear resistance influence dentures' longevity. Also, DB dimensional stability after insertion is critical for the long-term use of CDs [48].

The wear resistance of 3D-printed teeth varies depending on the manufacturer and printing technology, even with standardization of the printing parameters [29]. According to an in vitro study, NextDent C&B MFH resin printed with DLP technology showed significantly lower wear resistance and fracture resistance than both Formlabs Denture Teeth Resin printed with SLA technology and conventional PMMA teeth. Moreover, the Formlabs printed demonstrated comparable strength and wear resistance to the prefabricated teeth [29].

Denture teeth fracture during clinical use or from sudden impact force is a frequent issue with removable prosthesis affecting the denture's longevity. As a result, it is advisable to choose teeth with high fracture resistance [29]. Additionally ,the CD base material needs to have a high elastic modulus to prevent wear, fracture, and permanent deformation from the stresses applied during mastication [73].

3D-printed resin specimens demonstrated lower flexural strength, hardness and elastic modulus values when compared with heat-cured specimens [74,75] and CAD /CAM milled denture resins [76]. Despite the lower flexural strength of 3D-printed resin, it still met the ISO requirements of 65 MPa. Regrettably, the average flexural strength decreased below the recommended value after thermal cycling, highlighting a crucial concern regarding the clinical performance of 3D-printed material in conditions that simulate the oral environment [2].

3D-printed resin's lower mechanical properties may be due to its composition, which uses acrylic esters in the monomer with low double-bond conversion compared to conventional resins. Thermal cycling affects the layering interface, where water sorption leads to resin swelling and layers parting away, affecting the flexural strength of the resin. Absorbed water acts as a plasticizer, damaging polymer chains through ester bond cleavage and deteriorating mechanical properties [50].

SEM analysis revealed voids at the fracture site of DLP/SLA printed objects, which can reduce interfacial bonding layers, lead to delamination, and initiate fractures. A void within the bulk of the specimen may act as a flaw, while the specimen peripheries may act as the origin point of the fracture [50,77]. Void formation in printed resin occurs due to shaking the resin container and pouring it into the printing tray vat under atmospheric pressure, which can allow air bubbles to accumulate. In addition, during printing, the build platform detaches from the vat bottom, creating a negative pressure and allowing air to penetrate the resin. The formation of voids depends on the resin viscosity, where a low viscosity resin can improve the isotropy of the printed object [50,77].

The mechanical characteristics and durability of CAD/CAM PMMA was higher When compared to heat-cured PMMA [78]. The use of high pressure and temperature for the fabrication of the CAD/CAM PMMA leads to a higher degree of monomer conversion and the development of longer polymer chains than the conventional heat-activated PMMA, resulting in less porosity and a reduction in free volume [44]. A systematic review reported a mean flexural strength value for nine different CAD/CAM milled material of 120.61 MPa and 69.15 MPa for the 3D-printed (NextDent Base) product [79]. These values vary depending on the manufacturer and testing conditions (wet or dry), as 3D printed samples had lower wet strength values [4].

Regarding long-term dimensional stability, it was found that the 3D-printed mandibular DB is less dimensionally stable than the maxillary DB [47,48].

Surface Characteristic and Biocompatibility

The surface characteristics of the DB affect water sorption, microbial cell adhesion, staining, and denture hygiene [60]. It was proven that the DB surface roughness is directly related to hydrophobicity. A rough and hydrophobic surface promotes plaque adhesion [48]. With hydrophobic microorganisms such as Candida albicans easily attach to hydrophobic surfaces. Increased surface energy, particularly above 50 mJ/m2, is crucial for adhesion via the formation of glycoprotein pellicle precursors [48,60]. Applying a hydrophilic glaze coating to the denture surface has been shown to improve surface smoothness and reduce Candida albicans adhesion [44,48,80].

Based on in vivo studies, an accepted surface roughness threshold is (R_a = 0.2), below which no reduction in bacterial accumulation is expected. However, an increase above this threshold resulted in a concomitant increase in plaque accumulation [81].

On the contrary, an in vitro study associated the increased microbial cell adhesion with mucin adsorption rather than surface roughness [82]. The microbial cells adhesion was significantly higher in 3D printed resin compared to heat curing, whereas CAD/CAM milling resulted in a significant decrease in microbial cell adhesion. The results suggest that 3D printing may increase the risk of denture stomatitis, whereas CAD/CAM milling may reduce it compared to the conventional heat-curing method [82].

Color stability

The color stability of denture teeth is essential for optimal esthetics, as color alteration signifies material aging or deterioration. Patient satisfaction and quality of life is affected by the color stability and esthetics of the removable prosthesis [83].

Unfortunately, 3D printing resin has the disadvantage of poor color stability [84,85]. In contrast to SM, which involves using a resin disk that is polymerized at high temperature and high pressure with stable predetermined properties, AM may exhibit varying color stability and polymerization rates depending on the post-curing process [86,87].

Typically, printable resins have lower filler volume, which helps maintain low resin viscosity throughout the printing process and create a smooth surface finish [85,88]. Current printable resins contain 30–50 wt% filler [89,90], compared to 80–85 wt% for resins used in subtractive manufacturing [88]. Resin-based materials with lower filler volumes absorb more water, leading to hydrolytic degradation and ultimately to a greater susceptibility to staining [88].

The lower filler content in the resin makes it less wear-resistant and more prone to surface deterioration over time, which affects the material color stability. Surface deterioration is associated with the residual monomer content of the resin. Denture resins with high levels of residual monomer may undergo water sorption and expansion, leading to degradation of the surface and mechanical properties [85,88]. By acting as a plasticizer, the absorbed water breaks down ester bonds in the polymer chains, causing damage to the chains and decline in the mechanical properties [50].

Moreover, the surface characteristics and mechanical properties of 3D print resin differ significantly depending on the manufacturer [29,91].

The color stability of CAD/CAM milled denture resins was non-inferior to conventional heat-cure resins, while 3D printing denture resins showed a significant color change in comparison [92]. It was found that the increasing the post curing time improved the color stability of 3D printed tooth-colored resin by increasing the degree of conversion, wettability, and surface integrity [86].

Another inherent disadvantage is the incomplete polymerization at the interface between the printed layers, along with the presence of microporosities and residual monomers, which can eventually make 3D printed material more susceptible to staining [88]. In addition, settling down of filler particles during storage can lead to printing inhomogeneous layers, impaired polymerization and further exacerbating surface deterioration [85]. On the contrary, an in vitro study found no difference between milled and printed DBs in terms of surface roughness and biocompatibility [76].

ADVANTAGES OF CAD/CAM DENTURES

The CAD/CAM technology and the digital workflow can eliminate the traditional processing drawbacks, reduce the number of visits, save chair-side time and enable

timely delivery of the prosthesis for patients with time constraints [1].

Moreover, a duplicate denture is easily fabricated thanks to the advantage of the stored denture data. An intraoral scanner is used to scan the patient's existing CD and print a monolithic try-in duplicate which is used to capture final impression and interocclusal records. The trial denture is scanned using an intraoral scanner.[93]. Also, a fully digital approach using intraoral scanner can be used [94].

CAD-CAM manufacturing showed improved accuracy and retention compared to traditional processing, which can be explained by the absence of polymerization shrinkage.

Unlike 3D-printed dentures, milled dentures have superior mechanical qualities, including flexural strength, flexural modulus, yield strength, toughness, surface characteristics, and color stability. However, in terms of trueness, 3D-printed DBs were found to be better than conventional DBs [23].

3D printing offers several advantages over milling technology. First, less resin is required for printing compared to milling, and the cost of a printer is a fraction of the cost of a milling machine. Additionally, 3D printed denture are generally cheaper than milled dentures in terms of manufacturing costs for equipment and materials [23]. However, compared to conventional manufacturing, both milling and 3D printing required substantially fewer laboratory expenses overall [95].

DISADVANTAGES OF CAD/CAM DENTURE

The literature has highlighted several clinical drawbacks of CAD/CAM dentures, including frequent need for immediate relining, higher cost, material waste, increased occlusal vertical dimension, and compromised visual and speech aspects.

Drawbacks inherent to the milling process are material waste, wear of milling tools, and accessing undercut areas presents a challenge due to factors such as the size of the milling bur, the number of milling axes, and the limited movements of the machining axes [13].

The unpolymerized resin is 3D printed and polymerized by an ultraviolet (UV) or visible light source. The printed object is in green state and a post-polymerization stage of UV light irradiation is also required, hence polymerization deformation may occur [96]. Non-polymerized photosensitive liquid resin in printed dentures has the potential to create a negative reaction on the patient’s mucosa and/or the technologist’s skin [13].

Another limitation of AM is the staircase effect on the printed object’s surface. Unless layering thickness is set to the finest resolution, the finished product will still have a staircase effect due to the layer-by-layer nature of AM. This will, however, significantly increase the production time and cost [64].

The process of digital denture fabrication may have some disadvantages, nevertheless, the above-mentioned benefits and especially increased level of patient satisfaction can help to overcome the other disadvantages.

FUTURE DIRECTIONS

In an ongoing effort to improve provisional dental resins with an emphasis on strength, esthetics and biocompatibility, various materials have been used to reinforce dental resins such as metals, fibers, and oxides such as aluminum, zirconium, and titanium with less than optimal outcomes [97].

Recently, nanoceramic filler has been added to the resin matrix of 3D printable resins to improve the filler content and mechanical properties. They are suitable for fabricating permanent crowns, partial coverage restorations or long-term temporary bridges [40,88]. The concentration of nanofiller has been found to be directly related to the mechanical properties of composite resins. Wear resistance and physical qualities are usually improved with increased filler content which potentially can improve the denture’s longevity and the patients’ satisfaction [98].

However, these nanoscale particles can enter the bloodstream from the denture base or be inhaled. Alarming concerns have been raised about the integration of nanomaterials into denture base resins due to their nanosize, unpredictable health consequences, and potential accumulation in organs [98,99].

4. Conclusion and Recommendations

Dentistry has shown a remarkable willingness to adapt to the rapid expansion of 3D printing materials, methods, and workflows. However, the main clinical limitations,

including esthetic appearance, wear resistance, wet strength, and dimensional accuracy, are hindering the long-term use of 3D-printed dentures in the patient's mouth. However, these limitations may change with the rapid evolution of 3D printers and materials. Based on our findings, further investigation is recommended on an optimum printing angle for accurate CDs. More clinical studies are needed to investigate the clinical performance of poly-jet 3D printed dentures. Additionally, the literature is lacking in vivo studies on dentures' color stability and biocompatibility. Comparison between 3D printed denture teeth from ceramic nanofilled resin with provisional 3D denture teeth resin, crosslinked teeth and milled teeth is recommended. More investigation is needed to understand the long-term efficacy of different filler materials, concentrations, clinical significance and any possible health hazards related to the fillers.

Competing interests
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SB, Conceptualization, database searching, manuscript writing and is the corresponding author. MA, Database searching and manuscript writing. KZ, Supervision and manuscript revision

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