3D Printing of Dental Prostheses

Subjects: Dentistry, Oral Surgery & Medicine

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Revolutionary fabrication technologies such as three-dimensional (3D) printing to develop dental structures are expected to replace traditional methods due to their ability to establish constructs with the required mechanical properties and detailed structures. Three-dimensional printing, as an additive manufacturing approach, has the potential to rapidly fabricate complex dental prostheses by employing a bottom-up strategy in a layer-by-layer fashion. This new technology allows dentists to extend their degree of freedom in selecting, creating, and performing the required treatments. Three-dimensional printing has been narrowly employed in the fabrication of various kinds of prostheses and implants. There is still an on-demand production procedure that offers a reasonable method with superior efficiency to engineer multifaceted dental constructs.

Keywords: 3D printing ; dental prostheses ; dental implants

1. Introduction

Shifting from a traditional and manual workflow to a digital one is one of the major tasks of the dental community in today's world. The integration of new technologies, techniques, and instruments, which can be known as a routine practice, is the backbone of such shifting. In the last decade, the field of restorative dentistry has been significantly impacted by the emergence of novel, fully automated, and rapid prototyping techniques to design and fabricate dental prostheses in a three-dimensional (3D) manner [1]. Digital dentistry has witnessed enormous progress, especially with regard to computer-aided design (CAD)/computer-aided manufacturing (CAM) imaging and milling systems, which addressed many challenges in clinical dentistry [2]. Three-dimensional printing is an additive manufacturing procedure included in the most recent wave of technological progress [3]. Nowadays, a wide range of dental treatment trials, including orthodontics, dental implants, mandibular reconstructions, prosthodontic rehabilitation, surgical, and nonsurgical endodontics, have extensively exploited 3D printing technology [4].

This technique utilizes CAD to produce complex 3D constructs with desired geometries, allowing for a highly efficient, low-cost, and patient-specific design approach with the potential for rapid prototyping. Indeed, the advent of novel 3D printing methods for dental application and the availability of related products in the market has attracted attention to this technology, due to its utility and burgeoning research [5][6]. Benefiting from 3D printing, clinicians may repair and replace damaged dental structures using specific biomaterials [7].

Unlike the 3D printing of complex and detailed structures, such as dental casts [8][9], orthodontics [10][11], and surgical guides [12], the process of fabricating single-unit crowns is relatively simple, allowing clinicians to perform same-day fabrication. It only takes a few minutes to scan a 3D model and send it to a chair-side 3D printer to print a unit crown. The clinician can then easily remove the supports and instantly cement the printed prosthesis. This new procedure can enhance clinical productivity and efficiency by providing an alternative to the analog methods of fabricating provisional restorations. Despite the availability of this technology, it is still limited by issues with material compatibility, availability, cost-efficiency, and operator calibration [13]. Despite the existence of the technology that allows clinicians to carry out these procedures, there are still some bottlenecks, such as a lack of experience in applying the appropriate dental 3D printers and materials, in relation to compatibility, availability, and cost-efficiency, which should be addressed. In recent studies, dental prostheses have been obtained with precise 3D printing systems using a variety of materials, including zirconia [14], pure titanium [15], and polymer-based composites [16].

In general, 3D printing is becoming increasingly popular in dentistry because it allows practitioners to create highly customized and precise dental prosthetics, such as crowns, bridges, and implants. This can be particularly beneficial for patients who have unique dental anatomy or who require customized solutions, due to injury or other conditions.

2. Application of 3D Printing in Dental Prostheses

Three-dimensional printing in dentistry, mainly when applied to the fabrication of dental provisional restorations (bridges and crowns), is new, with related studies dating as recently as 2013. Most of these studies focused on the fit of 3D-printed restorations and compared their characteristics with those fabricated by conventional methods. Marginal and internal fit is identified factors that have a critical impression on the long-term achievement of dental restorations [17]. The marginal fit of restorations is highly related to their manufacturing technique [18]. Some parameters can influence the marginal fit of prostheses manufactured by 3D printing, such as type of resin, type of printing machine, device calibration, in terms of environmental temperature and moisture, and restoration shape complexity [19].

In a recent study, Lee et al. investigated the internal fit of dental crowns obtained by 3D printing and the CAD/CAM milling method using stainless steel and vinyl-polysiloxane [20]. As a result, the mean discrepancy values were measured to be 141.1 and 91.1 µm for the crowns fabricated by two brands of 3D printing systems and 171.6 µm for those fabricated by the milling system. Furthermore, the internal and marginal fit of the fabricated crowns obtained from 3D printing systems were significantly improved, compared to those fabricated by CAD/CAM milling system. Tahayeri et al. optimized the 3D printing of dental materials for bridge restorations and provisional crowns using a low-cost stereolithography 3D printer and compared their mechanical properties to conventionally cured provisional dental materials [21]. Fourier-transform infrared spectroscopy (FT-IR) analysis and three-point bending methods were employed to evaluate the degree of conversion of the resin and the peak stress and the elastic modulus of 3D-printed bars, respectively. They also compared the obtained results with two conventionally cured provisional materials, Jet®, Lang Dental Inc., Wheeling, IL, USA, and Integrity®, Dentsply, Charlotte, NC, USA. As reported, there was no direct correlation between the printing layer thickness and peak stress or elastic modulus. The 3D-printed models showed similar and significantly higher peak stress compared to Integrity® and Jet®, respectively. Furthermore, compared to Jet® and Integrity®, the 3D-printed samples had comparable and significantly lower elastic modulus. Interestingly, the 3D-printed samples also showed an enhanced degree of conversion than those of Jet® and Integrity®.

Similarly, Alharbi et al. compared the effects of 3D printing and milling methods and different finish line designs on the marginal and internal fit of interim restorations [22]. As reported, the mean internal gaps for milled restorations were 89, 177, 185, and 154 µm, fabricated on a knife-edge (KE), chamfer (C), rounded shoulder (RS), and rounded shoulder with bevel (RSB) finish line designs, respectively. On the other hand, these values for 3D-printed restorations were reported to be 66, 149, 130, and 95 µm, respectively, for KE, C, RS, and RSB, indicating the significantly lower internal gap of 3D-printed restorations, compared to those obtained from milling methods. Furthermore, the 3D-printed restorations showed lower mean absolute marginal discrepancy (30, 41, 30, 28 µm) than the milled restorations (56, 54, 52, 38 µm) for KE, C, RS, and RSB, respectively. The aforementioned results designate that the finish-line design techniques have a lower impact on the fit than the fabrication methods [22].

In another study, Chaturvedi et al. evaluated the marginal and internal fit, using finish line chamfer, rounded shoulder, and rounded shoulder with bevel, of the provisional crowns obtained by three-dimensional (3D) printing, compression molding, and milling methods [23]. The result of that fabrication method and finish line design has a substantial effect on the internal and marginal gap. The minimal marginal gap and the best internal fit in all various finish lines belonged to the 3D printing methods, in comparison with compression molding and milling methods [24].

Despite providing a rapid technique for the fabrication of zirconia dental restorations, CAD/CAM milling systems present a few disadvantages, such as material waste, processing defects, such as microscopic fractures, and inadequate accuracy [25]. Ebert et al. employed direct inkjet 3D printing to fabricate all-ceramic dental restorations using zirconia-based ceramic suspension as the source material [26]. The obtained 3D-printed dental crowns possessed high mean fracture toughness (K_{Ic} = 6.7 $MPam^{0.5}$) and characteristic strength of the ground bars (σ_0 = 763 MPa) with a 90% confidence interval of [678;859]. Revealed by scanning electron microscopy (SEM), homogeneous cross-sections were apparent, with no significant defects (except for a few process-related ones) on the surface of the specimens. In view of cost-efficiency, this promising method consumes a minimum number of materials.

To further evidence the superior efficiency of 3D printing procedures for the manufacturing of dental prostheses compared to conventional techniques, Eftekhar Ashtiani et al. employed intraoral scanning and 3D printing of the pattern for the fabrication of intracoronal restorations and compared their dimensional accuracy to those obtained from the conventional fabrication of a resin pattern [27]. Interestingly, the conventional method resulted in more accuracy than the 3D printing, regarding impression making and the fabrication of intracoronal restorations. However, the fabricated restorations with both methods yielded a clinically acceptable fit.

Similarly, Homsy et al. compared the internal and marginal fit accuracy of lithium disilicate-based inlays manufactured with conventional milling and 3D printing methods [28]. Here, the marginal and internal fit accuracy of the inlays fabricated by digital impressions and subtractive milling of wax patterns were significantly better than those of the conventional impression/fabrication and 3D printing techniques. It is worth noting that the fit values measured for 3D-printed wax patterns were similar to those of the conventionally waxed inlays.

Fathi et al. reported similar results, stating that the 3D-printed wax crowns were more accurate, in terms of internal and marginal fit, than milled and manually fabricated wax crowns [29]. Furthermore, conventional hand carving and milling of wax crowns both resulted in significant discrepancies in occlusal gap points, when compared to additive methods, demonstrating 3D designing and manufacturing of wax patterns for complete crowns as a more accurate procedure [30].

As the fracture load is a critical characteristic for dental restorations, it is crucial to assess this index for structures that novel approaches, such 3D printing, have manufactured [31]. To this end, Zimmermann et al. determined and compared the fracture load of crowns made of three particle-filled composite CAD/CAM materials, including Cerasmart (GC Corporation), Brilliant Crios (Coltène AG; Altstätten), and Lava Ultimate (3M ESPE), and one 3D-printed composite (els-3D Harz; Saremco Dental AG) as a function of three different material thicknesses (0.5, 1, and 1.5 mm) [32]. Amongst all groups, Brilliant Crios and els-3D Harz, respectively, showed the highest mean loading forces before fracture, which were measured to be 1580.4 N and 1478.7 N, with 1.5 mm thickness. The fact is that the fracture loading force mainly depends on the respective material and thickness; therefore, none of the 0.5 mm ceramic crowns (as group control) survived the fatigue testing, while all the resin-based crowns did. Consequently, regardless of the fabrication mode (CAD/CAM or 3D printing), the particle-filled composite resins may play an essential role in manufacturing minimally invasive restorations with good mechanical properties [32]. A wide range of complications can be developed as consequences of the marginal discrepancy between the abutment and the restoration material [33].

Similar studies on the fabrication of CAD/CAM-based temporary crowns and evaluation of the internal matching were conducted by Lee et al. First, they scanned the ready-made stainless model using digital scanners and designed it with software CAD/CAM. Then, they used 3D printers to fabricate dental crowns. Zirkonzahn (3D milling system), Stratasys, and Dentis (3D printing system) technology were used to fabricate the crowns [20]. Vipi block, VeroGlaze MED620, and ZMD-1000B resin were applied in the fabrication. For each group, ten files were made. The mean ± standard deviation (SD) values of marginal discrepancy were found to be 171.6 ± 97.4, 149.1 ± 65.9, and 91.1 ± 36.4 for the CAD/CAM milling group, Stratasys group, and Dentis group, respectively. *p*-values for the 3D printing groups (consisting of Stratasys and Dentis groups) were lower, compared to that for the CAD/CAM milling group. According to the significant level of the *p*-value (a *p*-value less than 0.05 was considered significant), the mean discrepancy values were found to have statistically significant differences. Accordingly, a high level of completion is an advantage that makes the 3D printing method a suitable method to be applied in the production of dental prostheses, in addition to the interim restoration production [20].

The solidification of liquid polymer resins, including resins, photopolymers, and transparent resins, is a process in additive manufacturing performed by UV light in digital light processing (DLP) printing technology [34]. Applications of DLP in dentistry include the fabrication of dental models, dental implants, cochlear implants, and dental restorations. Moraru et al. used this technique to fabricate dental prostheses [35]. The advantages of this method are its high accuracy in printing different parts, as well as the appropriate surface of the final product [36]. Son et al. fabricated three 3D printing Interim dental crowns by SLA and DLP and milling methods. They focused on the comparison of intaglio surface trueness at each implant. They used CAD/CAM to design and model the crowns, as in previous studies. In the fabricating procedure of interim dental crowns, 3D printing technologies presented higher accuracy than milling [37].

Firlej et al. investigated five materials for 3D printing applications. These resins were UV-curable form. Isopropyl alcohol was sprayed on all of them. This removed the rest of the resins on the implants. They evaluated the effect of artificial aging on the quality of materials in various implants [38]. In some cases, both milling and 3D printing methods are clinically acceptable. For example, H Galeva et al. compared the internal and external accuracy fit of metal-ceramic fixed prosthetic constructions. Additionally, the temperature influence evaluations showed that the differences were not noticeable [39].

Temporary restoration modeling and fabrication are important in various dental applications. Mohajeri et al. investigated the effect of conventional fabricating methods against 3D printing on the marginal fit [40]. By utilizing these three fabrication methods, the restorations were generated via clinically suitable marginal fit.

A surgical guide in dentistry is a template that is used to accurately position dental implants in the jawbone [41]. Three-dimensional printing can be used to fabricate surgical guides by creating a physical model of the patient's jaw and teeth based on a digital 3D scan [42][43]. The guide is then created by slicing the digital model and exporting the slice data to a 3D printer [44][45]. Here is a step-by-step overview of the process:

- Digital 3D scan of the patient's jaw and teeth: The first step in fabricating a surgical guide using 3D printing is to obtain a digital 3D scan of the patient's jaw and teeth. This can be achieved using a variety of technologies, including CBCT and intraoral scanners.

- Design of the surgical guide: Once a digital 3D scan has been obtained, the next step is to design the surgical guide using specialized software. This involves creating a virtual model of the patient's jaw and teeth and then planning the placement of the dental implants based on the specific needs of the patient.

- Slicing the digital model: The next step is to slice the digital model of the surgical guide into layers, which can then be exported to the 3D printer. This process involves specifying the thickness of the layers and the type of 3D printing technology to be used.

- 3D printing: The slice data is then sent to the 3D printer, which creates a physical model of the surgical guide using a variety of materials, such as plastic or metal.

- Post-processing: Once the surgical guide has been printed, it may need to be post-processed, in order to smooth out any rough edges and ensure that it is accurate and ready for use. This may involve sanding, polishing, and sterilizing the guide.

- Use in surgery: The surgical guide is then used during the actual implant surgery to accurately position the implants in the jawbone. The guide helps the surgeon to place the implants in the correct location, ensuring that they are properly aligned and positioned for optimal function.

Three-dimensional printing can also be used to fabricate aligners, which are employed in orthodontic treatment to straighten teeth [46][47]. The process begins by creating a 3D model of the patient's teeth using a digital impression or a physical impression that is scanned into a computer [46]. The 3D model is then used to design the aligners, which are customized to fit the patient's teeth and apply the necessary forces to move the teeth into their desired positions [48]. The aligners are typically made of a clear, biocompatible plastic material that is suitable for long-term wear in the mouth. Once the aligners have been designed, they can be fabricated using a 3D printer. The finished aligners are then sent to the orthodontist, who gives them to the patient to wear, according to a prescribed treatment plan [46][49].

There are a few limitations to the use of 3D printing for the fabrication of dental surgical guides and aligners in dentistry [41][42][44][45][50][51]:

Material properties: The properties of 3D-printed materials may not be suitable for all dental surgical applications. For example, 3D-printed surgical guides may not be as rigid as those made from other materials, such as stainless steel.

Accuracy: While 3D printing can produce objects with high levels of accuracy, the accuracy of the final printed product may be affected by factors such as the resolution of the printer and the quality of the 3D model used as a reference.

Time: Three-dimensional printing can be a time-consuming process, especially for large or complex objects. This may not be practical in cases where time is of the essence, such as in emergency surgery.

Cost: Three-dimensional printing can be an expensive option, compared to other manufacturing methods, especially for large volume production.

Regulatory considerations: There may be regulatory hurdles to overcome, in order to use 3D-printed dental surgical guides and aligners in clinical practice, as they may be considered medical devices. This may require additional testing and documentation to demonstrate their safety and effectiveness.

There are a variety of clinical case reports regarding the use of 3D printing for dental prosthetics. Three-dimensional printing can be clinically used to create crowns, bridges, and dentures that are custom fit to a patient's teeth, which can improve the comfort and aesthetic appearance of the restoration [52][53]. For example, Srinivasan et al. performed a double-blind, randomized, and crossover clinical study to show the differences between 3D-printed and milled complete removable dental dentures [53]. They revealed that the cost and time of the workflow are likely same for two groups of patients [53].

One of the important clinical applications of 3D printing in dentistry is the use of this technology for the fabrication of a surgical guide and aligner. Surgical guides created by 3D printing can be used to accurately place dental implants in the jawbone, which can help to reduce the risk of complications and improve the overall success of the surgery. For example, there is a case report by Zoran et al. in which a guide was created by 3D printing technique for implant placement [54]. Its results showed that, considering both surgical and prosthetic aspects, the 3D-printed surgical guide could facilitate having an optimal positioning of the implant [54].

The fabrication of custom dental implants is another clinical application of 3D printing in dentistry. Printing can be used to create custom dental implants that are tailored to the specific shape and size of a patient's jawbone, which can improve the fit and function of the implant. Par et al. reported a case study on 3D-printed titanium implant [55].

At the clinical stage, 3D printing has various pros and cons [56]. The typical advantages can be attributed to the customizability, flexible and fast design and production, long-term cost, ease of access, minimizing waste, and being environmentally friendly [56][57]. Similar to other fabrication methods, 3D printing has its own drawbacks for clinical applications, including limitations in the material selections, possible post-processing requirements and probable design inaccuracies [56][58].

3. Dental 3D Printing Materials

More specifically, there are a number of materials that are commonly used in 3D printing for dental prosthetics, including acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and a variety of resins. Several synthetic polymers, including poly(ethylene glycol) (PEG) and poly(vinyl alcohol) (PVA), have also been exploited in the 3D printing of dental biomaterials, due to their tailorable mechanical and degradational properties [24][59]. Some newer materials are being developed and used in 3D printing for dental prosthetics. One example of a new material that has been used in the 3D printing of dental prosthetics is bioceramic. Bioceramic materials are ceramic materials that are biocompatible, meaning they are safe to use in the human body [60]. They have been used in a variety of medical applications, including dental prosthetics, due to their strength, durability, and ability to bond with living tissue. Bioceramic materials are also resistant to wear and corrosion, making them a good choice for use in dental prosthetics that will be subjected to high levels of stress and exposure to oral fluids. Some examples of bioceramic materials that have been used in the 3D printing of dental prosthetics include zirconia, alumina, and hydroxyapatite [61][62].

Composite materials that combine ceramics with other materials, such as plastic or metal, are also good options for the 3D printing of dental prosthetics [63]. These materials offer improved strength, durability, and aesthetics, making them suitable for a wide range of dental applications. Additionally, some of the newer 3D printing technologies, such as SLS and electron beam melting (EBM), allow for the use of metal materials, such as titanium and cobalt-chrome, which can be used to create more durable and biocompatible dental prosthetics.

In addition to different fabricating technologies, different materials present other mechanical properties, such as thickness. For example, in a recent study, three resins, including bisacrylic, acrylic, and PMMA, were used for microcomputed tomography of 3D-printed dental crowns. Utilizing them with 3D printing technology presents higher film thickness in dental crowns [64].

3.1. Thermoplastic Polymers

Among the various options available for the fabrication of dental 3D printable substances, polymer-based materials are the most commonly utilized materials. Photopolymerization is the most feasible technique for the fabrication of dental resins or polymeric 3D-printed materials [24]. A smoother surface, strong chemical bonding, suitable mechanical strength, and high-quality build resolution can be provided using photopolymerization [6]. Thermoplastic polymers are the most frequently used polymer-based biomaterials for dental 3D printing [65]. The filaments that make the main backbone structural compartments of thermoplastic polymers can flow through the nozzles by applying heat [66][67]. Among these polymers, polyethylene (PE), polypropylene (PP), PLA, and ABS are the most frequently used in the field of 3D printing of polymeric dental biomaterials [68]. Due to the non-toxic properties of PLA against the oral cavity, it is assumed to be more favorable for utilizing in 3D printing, compared to ABS [67][69]. Thermoplastic filament polymers with higher glass transition temperatures, such as polymethyl methacrylate (PMMA) and polyether ether ketone (PEEK), have been recently studied for the fabrication of dental 3D-printed materials [24]. Schönhoff et al. compared the amorphous polyphenylene sulfone (PPSU) with established semi-crystalline polyetheretherketone (PEEK). They found that PPSU can be a suitable material, instead of PEEK. They evaluated the mechanical properties that confirmed recently proposed research [70].

Wieckiewicz et al. [71] investigated the surface roughness, color stability, and elasticity of polyamide-12 (PA) versus polymethyl methacrylate (PMMA) denture-based material as a control. The results suggested that PA showed a higher susceptibility than PMMA to discoloration.

3.2. Ceramics

Compared to polymers, ceramics are less frequently used in 3D printing [72]. However, due to their unique properties, ceramics are good candidates to be utilized in stereolithography (SLA) and SLS, in which ceramic powder or a pre-sintered ceramic material are processed to form a structure with strong bonding [1][67][73][74]. A biocompatible microenvironment can be formed in ceramic structure by adding mineral substances, such as hydroxyapatite and β-tricalcium phosphate, which provide calcium and phosphate ions [75]. Moreover, the incorporation of calcium and phosphate mineral phases has been shown to improve cell-to-cell interactions and induce cell differentiation and proliferation, which makes these types of ceramics good candidates for craniofacial applications [76][77]. However, due to the challenges associated with the processing of ceramic powders to high-density structures, the products of the selective laser sintering of these powders are porous structures. Additionally, anisotropic shrinkage and stair-step effects can occur upon additive manufacturing approaches. The above-mentioned challenges have limited the ceramic utilization of ceramics for the development and fabrication of ceramic 3D-printed restorations [67][78][79].

3.3. Metals

Metals have been mainly used in selective laser sintering to fabricate dental 3D-printed materials [80]. In dentistry, metallic alloys, including nickel, cobalt-chromium, and titanium alloys have been vastly studied and used [81]. However, due to the possible allergic reactions in the oral cavity, scientists no longer suggest the utilization of nickel alloys in dental metallic materials [82]. Similar to ceramics, the fabrication of metallic biomaterials by selective laser sintering leads to porous products [83]. Due to the negative effect of porosity formation on the strength and resistance of 3D-printed materials, some solutions, such as equipping a vacuum pump with a sintering instrument, have been considered, in order to improve the quality of metallic dental prostheses [7][67][84][85]. Among metallic materials, cobalt-chromium and titanium are the most commonly used alloys for the fabrication of 3D-printed metallic prostheses, due to their strength and ductility [86]. Furthermore, various clinical trials in the field of maxillofacial prostheses have been performed on titanium alloys, specifically Ti_6Al_4V [1][67][87].

3.4. Others

According to SLM and SLS methods, there are some limitations in utilizing ceramics or metals materials [88]. This matter is because of the thermal shock conditions and high melting temperature in metals and ceramics, respectively [89]. Thus, researchers developed novel approaches to overcome these limitations. For example, in a recent study [90], a combination-producing method, called additive manufacturing, was utilized to make high-density zirconia dental crowns.

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