Review Article

Applications of 3D Printing in Restorative Dentistry: The Present Scenario

Essa M. Beleges[1*], Turki A. Khurayzi[1], Saud A. Dallak[1], Ramzi M.A. Hadi[1], Abdulrahman M. Akkam[2], Ayman J. Okiry[2], Osama A. Ageeli[3], Shankargouda Patil[4]

[1]Dental intern, College of Dentistry, Jazan University, Jazan, SA
[2]6th Year Dental Student, College of Dentistry, Jazan University, Jazan, SA
[3]General Practitioner, Ministry of Health, Jazan Dental Center, Jazan, SA
[4]Associate Professor, Department of Maxillofacial Surgery and diagnostic sciences, Division of oral Pathology, College of dentistry, Jazan university, Jazan SA

Abstract

The use of 3D printing has seen a rapid increase in dentistry. This technology offers a lucrative advantage of combining precision and customization with reduced labor and time consumption. It aids the creation of a digital workflow wherein every step is performed virtually without a need for multiple laboratory procedures. Reduced material consumption in additive manufacturing when compared to the traditional milling techniques also makes it a convenient option. However, the properties of rapid prototype materials are dependent on multiple factors. Research on their mechanical properties has been done and factors affecting the same have been determined to an extent. The many aspects involved in the printing of dental materials make it necessary to exhaustively research the influence of each on different materials and techniques of manufacturing. This review aims to describe the present applications of additive manufacturing technologies in fabricating dental restorations. Studies that have explored the accuracy and properties of the materials used at each step, from creating tooth dies to a fixed prosthesis, and compared them with presently used methods have been discussed. The factors that influence the fabrication accuracy and mechanical properties have also been described. Though further studies on the material, technical and biological influences are needed, the present research seems promising. This technology can change the techniques used in restorative dentistry for the benefit of both the patients and dentists alike.
Keywords: 3D printing, additive manufacturing, restorative dentistry, dental restorations, fixed prosthesis.

INTRODUCTION

Three-dimensional printing, also known as rapid prototyping or additive manufacturing, is a technology that is being gradually integrated into everyday lives and dentistry is no exception. The accuracy and customization incorporated into products made by 3D printing make it an ideal technology for dental sciences. According to the international organization for standardization and the American Society for Testing Materials, the 3D printing technologies based on geometrical representation, create objects by successive addition of material [1].

Various techniques are available for 3D printing of which the most commonly applied to restorative dentistry use principles of material extrusion, powder bed fusion, directed energy deposition, material jetting, or photopolymerization. Most techniques used in dentistry rely on a combination of principles. The technique of Selective Laser Sintering/Melting (SLS/M), for example, uses a directed energy source (the laser) and the fusion of particles takes place on a build platform with powder deposited on it (powder bed fusion). Once the metal particles are sintered together, a roller simply removes the excess powder from the layer. The build platform then descends a height identical to the thickness of the layer just formed and another layer of powder is deposited on the already formed layer [2]. Most technologies use a build platform on which the material is deposited in the form of a single layer and then processed or cured followed by successive layers which result in a 3D object.

Additive manufacturing offers various advantages over the currently used subtractive/milling techniques. It allows the production of complex geometries with ease, reduce wastage of material which

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is generally lost to milling, allows the production of details with accuracy, and do not present problems such as microcrack propagation due to forces applied when milling restorative materials [3-5]. Despite the increasing popularity of the technique, its application in restorative dentistry and research in the area has been limited. The purpose of this review, therefore, is to scope areas of application and highlight the factors influencing the dental materials made using this technology.

Tooth Models/Dies

Combined with the use of either an intraoral scanner, the dies for a tooth can be 3D printed without the need for a plaster model. Conventionally, plaster models are considered as the gold standard on which wax patterns/copings for intracoronal/extracoronal restorations are fabricated. In a study, different types of rapid-prototyped dies were compared to the plaster models. Three techniques of digital light processing (Photopolymerization), Jetted photopolymer, and stereolithography were used to print the models [6]. The differences in the models' crown heights and widths, when compared to the original, were -0.02mm and 0.08mm respectively for jetted photopolymers, 0.25mm and 0.05mm for stereolithography, and 0.04mm and 0.05mm for digital light processing technologies respectively. The authors of this study did not find any clinically significant difference between plaster and 3D printed casts. Similar results are seen in the study by Brown *et al*. where digital models and DLP and polyjet printers were compared to stone models. They found no significant difference between the models except the crown height between the plaster models and DLP models. The authors concluded that both DLP and polyjet printers were viable tools for clinical application [7].

A study, done by using the FormLab printer (Form Labs, USA), tested the accuracy of 148 die and arch models produced with rapid prototyping. Here, the printed models were scanned post-processing using a desktop scanner (3Shape, Trios, USA), and the .stl files were compared to the originals. These models were printed at layer thicknesses of 25 µm, 50 µm, and 100 µm. Those printed at a layer thickness of 25 or 50 µm were found to be in the clinically acceptable error margins by the author. The acceptability for accuracy was limited to 50 µm for the dies and 100 µm for the full arch models [8].

On the contrary, a study that used digital superimposition of models printed using 3 different printers (Objet EDEN260V, Promaker- D35 and LC-3D print) based on photopolymerization and polyjet printing technologies, found significant volumetric differences between stone casts and 3D printed casts. The least difference was found for the casts that were made with an ultraviolet polymerizing polymer [9]. This study, however, does not take into account layer thickness which, as demonstrated by the previous study can affect the accuracy and dimensional precision of the models.

Wax Patterns, Inlays and Onlays

Fabrication of wax patterns is an important step in making a cast restoration. They can be made by hand, milled or can be 3D printed, usually by the material extrusion technique. Rapid prototyped wax patterns have been fabricated for implant abutments, onlays made with lithium disilicate, metal copings and metal crowns [10–13]. Studies found the wax patterns to be adequate for clinical use though they were not always superior to the ones made by milling or by hand. Inlays and onlays have been printed using resins and wax patterns for ceramic inlays have been manufactured using rapid prototyping [14–16]. The accuracy of these has been measured against milled restorations and conventional techniques. Studies have found that the wax patterns made by 3D printing offer an inferior result compared to conventional or milling techniques. A comparison of inlays/onlays made on six different teeth with milling or 3D printing was evaluated for marginal and internal fit. The fit of the restorations made by rapid prototyping as the internal gap was reduced by 40-60% than the milled group [15]. Mechanical properties of 3D printed indirect polyetheretherketone (PEEK) inlays were found to be adequate for clinical use with an ability to withstand chewing cycles but need improvement in terms of accuracy and esthetics.

Single Tooth Crowns

Fabrication of single-tooth restorations using additive manufacturing has been done using inkjet printing, SLS, and DLP techniques. The materials which have been used for printing include metals, ceramics and hybrid resins. Ceramic crowns have been made using material extrusion techniques. In vitro fabrication of single-tooth crowns using viscous solutions of dental porcelains followed by post-fabrication processing was found to have the potential for application in the clinical setup. Ebert *et al*. fabricated crowns that were made using direct inkjet printing to overcome the shortcomings of the subtractive method[5]. They found that the posterior crowns fabricated with this method had a high accuracy with minimal material consumption. The strength and fracture toughness of these specimens was comparable to that of conventionally produced zirconia. Another technique, used to fabricate in vitro porcelain crowns, is the use of solid freeform fabrication in which a very viscous material is extruded onto a platform at a very low extrusion pressure and a 'green' model is fabricated. This model consists of dense but unsintered porcelain which holds its shape due to the rheological properties of the solution. This technique was used to develop the initial 'green' model from a digital file in just 30 minutes [17]. The model was then sintered and solid tooth structures, as well as a crown, were

fabricated. These models showed uniform shrinkage and properties were comparable to conventional materials. Both the studies show that additive manufacturing as a fabrication procedure is faster, simpler, economical and is not as labor-intensive as the conventional laboratory processes.

Tooth-colored single tooth restorations have also been fabricated by additive manufacturing of photopolymerized resins though not as extensively as metal restorations. Studies have evaluated the dimensional precision and mechanical properties of the resin restorations as affected by build layers [18, 19]. It was observed that layers built vertically that is, perpendicular to the load direction was able to withstand higher compressive forces compared to the horizontal layers. The build angle influenced the dimensional accuracy of the crown. On testing 9 different angles on crowns manufactured with stereolithography (SLA), it was found that a build angle of 120 degrees showed minimal deviation (0.029mm) from the original values when used with thin supports. This was evaluated using the digital subtraction technique. This angle also appears to offer the best self-support geometry [19]. When evaluating restorations made using digital light processing (DLP) technology with the same parameters, a build angle of 135 degrees was more favourable [20]. The build angle also had an impact on the marginal adaptation of DLP printed provisional crowns. A study evaluated the marginal, cervical, occlusal and axial gap with different build angles [21]. The results indicated that marginal, cervical and occlusal gaps tended to differ with build angles. The authors of the study concluded that an angle of 150 or 180 degrees was able to achieve the closest fit. A comparison of interim crowns fabricated with CAD/CAM and 3D printing technologies showed a significantly better fit of the 3D printed groups [22]. Of the two 3D printing technologies evaluated, the SLA printer showed less marginal gap than the one using material jetting but this difference was not evaluated for statistical significance.

Metal crowns are usually manufactured using laser sintering as the technology provides temperatures high enough to bring about sintering or melting of powdered metal. Studies that evaluate the accuracy and fit of the crowns have been done in vivo. The marginal adaptation of these crowns is similar to those fabricated conventionally [23-25]. Quante *et al.* evaluated 2 different alloys made by SLS for their marginal adaptation and fit (a Co-Cr alloy and an Au-Pt alloy) [23]. These parameters were evaluated after fabrication, after firing the veneer ceramic and just before cementation in vivo. The study found the clinical fit and accuracy of the crowns to be acceptable with the gap between the margins ranging from 74 to 99µm. The type of alloy did not influence the outcome [23]. The true evaluation however can only be done by comparison. A study by Huang *et al* compared base and precious metal alloys to evaluate the marginal fit of 3D printed crowns with those of conventionally manufactured with traditional laboratory procedures [25]. They found that the occlusal fit of the SLM Co-Cr crowns, the experimental group, was less accurate than the cast Co-Cr crowns. However, in the marginal fit of the restorations, the SLM Co-Cr crowns were superior to the traditionally made ones and comparable to the cast Au-Pt crowns. The crowns were made for anteriors, premolars and molars. The type of tooth did not seem to affect the accuracy of fabrication. In addition to traditional casting, Tamac *et al.* compared 3D fabricated crowns to ones made by CAD/CAM milling as well. They also found a significantly higher mean gap in the occluso-axial region and the occlusal surface for the 3D printed group [24]. The marginal gap however was similar to the other groups. This is confirmed in other recent in vitro studies as well. [26, 27]. However, when Chang *et al*. studied the differences in marginal discrepancy using 3D digital mapping for the conventional, SLS and the CAD/CAM group, gaps were the highest for the CAD/CAM group[28].

Metal copings made with Direct M *et al*. Laser Sintering (DMLS) when compared with traditional castings show similar results and the marginal discrepancy for these were within the clinically acceptable range [29-32]. A micro- CT analysis however showed that both milled and 3D printed copings had a significantly larger discrepancy than the controls which were made by casting and were dependent on the alloy used for fabrication [30]. When metal-ceramic restorations made with Co-Cr alloy were tested, the laser-sintered copings showed a significant increase in the marginal discrepancy after applying the veneer ceramic on the metal [33].

Follow up studies on the single metal-ceramic restorations show that these may have an extremely favorable outcome. Abou Tara *et al.* followed up 60 restorations for 47 months and found minimal failures (three) during the observation period [34]. The same group followed up over a longer period showed a survival rate of 81% for these crowns after 14.7 years [35]. 3D fabricated crowns, therefore, are viable, economical alternative to the traditional techniques of single tooth crown fabrication.

Fixed Prostheses
Many authors have studied the fabrication of 3-unit prosthesis using 3D printing. The technique commonly evaluated is the synthesis of a metal framework by using SLM by measuring the marginal discrepancy of the prosthesis to the die. They have been compared to traditional casting techniques as well as CAD/CAM milling techniques. Studying the marginal discrepancy amongst different fabrication methods revealed that the layer thickness affected this factor in the case of 3 unit prosthesis [36]. A significant

discrepancy exists when using a layer thickness of 50 µm than a 25 µm thick layer when examined with a stereomicroscope. However, both methods were judges to be clinically acceptable by the authors as none of the methods exhibited a discrepancy above 70µm which is well below the generally accepted limit of 120µm in the literature [36–40]. Another in vitro study which evaluated the SLM techniques against conventional methods found that the 3D printed Co-Cr prostheses were better adapted than the conventional ones at the margin ends with a mean marginal discrepancy of 43.93µm [41]. This study found the highest mean discrepancy of 74.73 µm in the zirconia group which used the milling process to manufacture the prostheses. A similar study that compared the 3D printed Co-Cr framework against a Co-Cr milled framework also found that the direct metal laser sintering (DMLS) group had a significantly better adaptation than the milled group. It fit better than the conventional techniques as well [42]. Contrary findings were reported in a study which compared DMLS to the lost wax technique [43]. The measurements were made with a digital microscope to measure the internal gap, the absolute marginal discrepancy and the marginal gap. The discrepancy was the highest in the internal gap with the value in the DMLS group (159.5µm) being nearly double that in the lost wax technique (82µm). A recent systematic review and meta-analysis on the reliability of metal 3D printed fixed prosthesis with respect to their marginal fit found them to be more accurate than conventionally fabricated ones for marginal adaptation [44]. The review however cautions that the method of evaluation of may influence the outcome of comparative studies.

An investigation of the effect of build orientation and layer thickness on the marginal fit and internal gap of the resin prosthesis, analyzed by a micro CT, indicated that these factors influence the fit of a 3D printed prosthesis made using DLP.[45] This study showed that the internal gap volume was the smallest for the 90 degrees orientation with the 100µm layer thickness which was less than the gap seen with a 50 µm layer thickness at the same orientation. The 45 and 60 degrees build orientation for the 50µm layer thickness groups showed a significantly smaller gap volume than the 100 µm layer thickness. The marginal fit of both groups was similar. Considering both the internal gap volume and marginal fit together, the authors recommended a build orientation of 45 and 60 degrees for the fabrication of a prosthesis by 3D printing. Further studies on the effect of the same factors when using other photopolymerization or jetting technologies can be done.

Ceramics undergo dimensional changes when they are sintered as do resins post-curing. Thus, the green models fabricated must be larger than required. A FEM study which evaluated the shrinkage rates for ceramic printed prosthesis found that these can shrink by a factor of 53.608% for a 3 unit bridge [46]. They found a similar shrinkage rate for ceramic crowns as well. The study recommended that printing prosthesis 1.861 times the desired size will result in a correctly sized prosthesis. Further studies on the effect of this shrinkage need to be carried out on the marginal adaptation and fit of the printed prosthesis. The post-fabrication processing of 3D printed resin prosthesis has an impact on the fracture load. This is also influenced by the type of resin used, the build direction, and aging of the prosthesis [47]. However, the flexural strength of these resins is better than the conventional [48].

A study assessed the clinical performance of fixed prostheses fabricated with the DMLS technique, when placed opposing the natural dentition and evaluated initially after 6 months and yearly thereafter over 5 years [49]. Evaluation was done using the modified clinical Ryge criteria which visually evaluates the fracture, marginal adaptation, and marginal discoloration [50]. They found no damage to the connectors but biological changes in the periapical region and development of carious lesions adjacent to the abutment teeth were observed in two cases. The five-year survival rate was determined to be 95.5 % for the DMLS fabricated 3-unit fixed prostheses by this in vivo study. Longer follow-up studies of patients are needed to compare and contrast the longevity of traditional, milled and rapid prototyped restorations and prostheses to determine their longevity in vivo.

CONCLUSION

Restorative Dentistry is a field that has multiple areas of application for rapid prototyping technology. The use of a digital workflow seems to be able to create a clinically acceptable result whether it is the creation of tooth dies, wax patterns, intracoronal or extracoronal restoration or even a fixed prosthesis. The mechanical properties of the dental materials made by additive manufacturing seem to present better results than the conventional though even this is influenced by various factors involved in the processing of the fabricated models, patterns or restorations. The accuracy of the restorations so manufactured and their mechanical properties, therefore, needs further research. There is also a lacuna in research when the effect of the method of processing raw materials for 3D printing is concerned such as different types of photopolymerization or material extrusion techniques, use of binders and post-fabrication processing. Studies in these areas will help understand the properties of 3D printed materials better by a dentist and help optimize their use in the clinics. Long term studies on the behavior of materials manufactured by this technique are also scarce and will help establish the acceptability of additive manufacturing among practitioners.

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