Review

Applications of three-dimensional printers in prosthetic dentistry

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Abstract: This narrative review aims to provide an overview of recent studies and case reports on three-dimensional (3D) printing, and to verify the applicability of 3D printers in the field of dental prostheses. This review was performed by conducting a search of PubMed. The clinical application of fabricating a prosthesis made with cobalt-chromium is considered possible depending on the material and hardware of the 3D printer. However, it is currently difficult to assess the clinical use of 3D-printed zirconia crowns. Further research is required, such as verification of materials used, margin morphology, and hardware. Clinically acceptable results have been reported for patterns using 3D printers. Interim restorations made using a 3D printer have been reported with good results that are considered clinically usable. Dentures made with 3D printers need further verification in terms of strength and deformation. Custom trays made with 3D printers are clinically useful, however, issues remain with design time and effort. Although several studies have reported the usefulness of 3D printers, further verification is required since 3D printers are still considered new technology.

Keywords: digital dentistry, three-dimensional printed crown, three-dimensional printed removable denture, three-dimensional printing

Introduction

Three-dimensional (3D) printing technology was developed in the 1980s. Initially, applications were limited due to issues such as product strength, accuracy, processing speed, and cost. However, research and development has proceeded around the world to produce real products using 3D printing. Currently, 3D printing is being utilized in the manufacture of various products due to improvements in processing accuracy and diversification of laminated materials [1]. In the field of dentistry, prostheses manufactured by 3D printers have a degree of freedom in design, and are considered to have a lot of potential. Digital dentistry was first used in the 1980s, and started with an attempt to make a dental prosthesis using a computer aided design/computer aided manufacturing (CAD/CAM) system [2-8]. The milling system used in dentistry, appeared in 1980 and was characterized by allowing ceramic inlays to be manufactured on the day cavities were treated [9-13]. The treatment was completed on the same day the inlay cavity was prepared, and it became the forerunner of the so-called same-day prosthesis. Since 2013, many papers (such as original articles, case reports, and reviews) on 3D printers in the dental field have been published (Fig. 1). At this stage, 3D printers were validated by making bone casts for oral surgical procedures [14-17], casts for simulating implant placement, and surgical templates for implant placement [18,19].

More recently, a technology known as 3D bioprinting, which allows the printing of cells and scaffolds together (biomaterials containing cells) or of cell aggregates without scaffolds, has been developed [20-23]. Furthermore, 3D bioprinting has permitted a wide range of materials with proven

osteoinductive capacity such as polycaprolactone, ceramic bases, calcium phosphate injectable pastes, and cell-laden hydrogels to be printed, although the printing still depends on the materials and methods as well as the capabilities of the printer hardware [24-28].

In terms of accuracy for manufacturing prosthetic devices, many studies have reported that the milling system has sufficient performance to manufacture dental prostheses [29-34]. In contrast, 3D printers are capable of forming complex shapes such as hollow interiors that were previously impossible with the milling system, and the capability could be considered as an advancement in reducing the weight of prostheses. In terms of consumption of materials, the milling system tends to waste materials because it cuts out large blocks when molding shapes. In this respect as well, 3D printers are considered economical as there is no excess material.

This review validated recent studies and case reports on 3D printing using a PubMed search, and considered the applicability of 3D printers in the field of dental prostheses.

Materials and Methods

This review was based on articles searched via the PubMed database and the period for the search was from June 1, 2020 to November 30, 2020. The reviewed articles were published between 2013 and 2020. The search keywords were “3D printing, three dimensional printing, crown, cast pattern, tray, denture, superstructure”, and different combinations of the keywords were used during the search.

Results

3D-printed master cast for definitive prosthesis

Applications of 3D printers for the production of fixed prostheses have been reported in the literature on production of master casts. Some studies (Table 1) evaluated master casts produced by a 3D printer and those made using a conventional superimposition method [35-37]. Two studies validated crowns, bridges, and inlays using 3D-printed casts [36,37], and the other one dealt only with crowns [35]. The three studies showed that master casts produced by the conventional method using gypsum and silicone elastomeric impression material were significantly more accurate than the casts made by a 3D printer. In the present circumstances, it is considered difficult to make a cast for a definitive prosthesis using a 3D printer. However, if it is possible to produce a highly accurate master cast that can be applied clinically using a 3D printer in the future, the master cast may be more useful than a milled master cast in terms of materials that can only be used in 3D printers and reduction of material consumption due to hollowing of the inside.

3D-printed prosthesis

Studies on the accuracy of prostheses produced by 3D printers are shown in (Table 2). A zirconia crown manufactured by a 3D printer was reported and its accuracy was verified [38,39]. In one of the above studies, 3D-printed zirconia crowns were evaluated for their internal and marginal adaptation [39]. The authors found that internal and marginal adaptation is not yet satisfactory for clinical application. Wang et al. evaluated crowns that were processed either with a 3D printing system or with a dental milling system, with the crowns being scanned using a dental laboratory scanner [38]. The study concluded that zirconia crowns produced by 3D printing meet the trueness requirements, and 3D printing may be suitable for fabricating zir-

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Fig. 1 The number of 3D printer manuscripts published each year

Table 1 Studies evaluating master casts

First author, year, [Ref.]	Product by 3D printer	Evaluation method	Result
Jang Y, 2018, [35]	Master cast	Evaluation by superimposing crowns	Although the fit of crowns fabricated based on the 3D printed models was inferior to that of crowns prepared with the conventional stone die group, values obtained with the 3D printing group were in the clinically acceptable range ($<120\ \mu\text{m}$).
Sim JY, 2019, [36]	Master cast	Evaluation by superimposing the master cast	There was no significant difference in accuracy between the plaster model and the digital model. However, the accuracy of the models made with 3D printers was low when compared with the stone model.
Choi JW, 2019, [37]	Master cast	Evaluation by superimposing the master cast	Conventional gypsum models showed better accuracy than 3D printed models.

conia crowns. Zirconia crowns made with 3D printers have received little attention, so it is not possible to determine whether 3D-printed zirconia crowns are in clinical use. However, future technological developments may lead to the clinical application of 3D-printed zirconia crowns.

In 2019, accuracy of crowns for upper molars manufactured by a conventional method (i.e. lost-wax casting), 3D printer, and milling system, was verified using 10 Co-Cr-Mo metal [40]. The margin gap was measured, and that produced by casting had a smaller gap than the one produced by milling system or 3D printer. However, no significant difference was found between the milled crown and the 3D-printed crown. The authors concluded that crowns made using these three methods were clinically acceptable. In studies that verified the accuracy of prostheses using a 3D printer, a large number of studies using cobalt-chromium were reported (Table 2). Many studies reported them to be clinically acceptable and/or better than milling [40-48]. Only two studies stated that they were clinically unacceptable [49,50].

From these studies, the clinical application of cobalt-chromium is considered possible depending on the material and hardware of the 3D printer. However, lack of research makes it difficult to assess the clinical application of zirconia. Additionally, it will be necessary to search for the best overall method such as materials to be used by the 3D printer to make the final prosthesis, shape of the margins, and printer hardware. Further verification is needed in the future.

3D-printed pattern for fixed dental prosthesis

The effectiveness of a fixed dental prosthesis using a pattern made by a 3D printer has been reported. A recent study reported that patterns of lithium disilicate for press were produced using three different methods, that is, by using 3D printers, milling, and conventional methods, where prostheses were produced using patterns, and that their effectiveness was verified [51]. All three patterns were found to be clinically acceptable. In addition, research in 2019 confirmed the accuracy of fixed dental prostheses cast using a wax pattern produced with a 3D printer [52]. This paper concluded that the pattern produced by the 3D printer was clinically acceptable and had a better marginal fit than the pattern produced by milling. Although it cannot be ascertained because the number of studies is small, it seems that pattern production using a 3D printer is clinically acceptable.

3D-printed interim restoration

Several papers have documented the production of interim restorations with 3D printers (Table 3) [53-58]. In 2017, interim restorations were

manufactured with a milling machine and a 3D printer to verify them [55]. The authors concluded that the restorations produced by both methods had the same accuracy. In addition, the paper indicated that the finish line morphology had a significant impact on accuracy.

Another study in 2018 also reported that interim restorations made with a 3D printer were clinically acceptable [56]. Also, in a study verified by a silicone replica method, when comparing interim restorations made with milling and by a 3D printer, it was found that the one produced by 3D printer was superior to milling in verifying marginal fit [53]. Other research that validated the internal fit of a interim restoration also reported that the interim restoration of a 3D printer was a better fit than the interim restoration made by a conventional wax-up method [58]. A study in 2017 verified the material properties of interim restoration produced by 3D printers [57]. In conclusion, it was suggested that 3D-printed interim restorations would allow sufficient mechanical properties for oral use.

From the findings of this research, the production of interim restoration with 3D printers is considered to be sufficient for clinical application. However, it is considered that the present superiority is not recognized when compared with interim restoration produced by milling system.

If it is possible to manufacture a interim restoration by 3D printer at a lower price and higher strength than one produced by the milling system, the versatility of using interim restorations made by 3D printing may be further expanded.

3D printers for manufacturing removable dentures

Regarding studies on applications of 3D printers for manufacturing dentures, it was reported that a casting metal framework made by a pattern with a 3D printer was compared with a metal framework using a conventional wax pattern, and the accuracy of metal frameworks or denture bases made directly by the 3D printer was compared with the conventional method. In 2019, research evaluating metal frameworks for partial dentures using a 3D printer was reported [59,60]. In a study verifying the accuracy of metal frameworks by 3D printing, it was concluded that the metal frames manufactured by 3D printing had better manufacturing accuracy and reproducibility than those manufactured by lost-wax casting [60]. In another study, a metal framework produced by 3D printing had clinically applicable indications, but a frame produced by casting was still slightly superior [59]. In research on the accuracy of denture bases made with 3D printers, the authors compared conventional denture bases made by heat-activated polymerization with 3D-printed ones, and examined their accuracy [61]. The result of this study was that denture bases made with 3D printers were

Table 2 Studies evaluating 3D printed prostheses

First author, year, [Ref.]	Product by 3D printer	Printing technology	Evaluation method	Result
Wang W, 2019, [38]	Zirconia crown	Stereolithography	The crowns scanned using a dental laboratory scanner	The trueness of the external surface of the 3D printed zirconia crowns was no worse than the corresponding trueness of the CAD-CAM crowns.
Li R, 2019, [39]	Zirconia crown	Stereolithography	The measured cement space of 3D printed zirconia crown	Internal and marginal adaptation of stereolithography-manufactured zirconia was not yet suitable for clinical application.
Chang HS, 2019, [40]	Co-Cr-Mo metal crowns	Selective laser sintering	The marginal gaps calculated using a 3D replica and mapping technique	The conventional lost wax and casting method had better accuracy in marginal gap than the 3D printing method, but the 3D printed crown was still applicable to dental restorations.
V Harish, 2014, [41]	Co-Cr copings	Laser sintering	Compared to the internal and marginal fit	The copings fabricated by Laser sintering technique showed better internal and marginal fit than the copings fabricated by the conventional casting technique.
Sundar MK, 2014, [42]	Co-Cr copings	Laser sintering	Compared to the marginal fit and microleakage	The copings fabricated using metal laser sintering technique had a better marginal fit and an observable decrease in microleakage when compared to the copings fabricated using the conventional lost wax technique.
Park JK, 2015, [43]	Metal copings	Direct laser metal sinterization (DLMS)	To assess the marginal and internal gaps of the copings	The coping produced by conventional casting had significantly better results than milling and DLMS, but the copings fabricated by computer-aided milling and DLMS fell within the range of clinical acceptance.
Huang Z, 2015, [44]	Single-unit crowns	Selective laser sintering (SLS)	Compared to the marginal and internal fit of single-unit crowns	The SLS system demonstrated better marginal and internal fit compared to the milling systems.
Ates SM, 2016, [45]	Metal frameworks	Direct laser metal sinterization (DLMS)	Evaluation of the marginal fit of frameworks and marginal gap values using a stereomicroscope	As an alternative milling technique, the DLMS technique exhibited satisfactory results and this CAD-CAM technique will become widely used in dentistry.
Gunsoy S, 2016, [46]	Co-Cr crowns	Direct laser metal sinterization (DLMS)	Evaluation of marginal/internal fit	Additive manufacturing crown performed better than milling one, but the CAD-CAM techniques did not exceed the conventional procedure with lost-wax and metal casting in the hands of an experienced dental technician.
Dahl BE, 2017, [47]	Single crowns with laser-sintered Co-Cr	Laser sintering	To verify internal fit (Measuring cement space using specifically designed computer software)	Additive manufacturing crown performed better than milling one, but the CAD-CAM techniques did not exceed the conventional procedure with lost-wax and metal casting in the hands of an experienced dental technician.
Lovgren N, 2017, [48]	Co-Cr single crowns	Laser sintering	Compared the marginal and internal fit	Laser-sintered Co-Cr crown copings showed increased surface roughness and better internal and marginal fit than copings produced by milling or milled wax/lost wax technique.
Kim KB, 2013, [49]	Co-Cr three-unit fixed dental prostheses	Direct laser metal sinterization (DLMS)	Examined marginal fit using a light-body silicone	The marginal fit of the DLMS system appeared significantly inferior compared to that of the conventional lost wax technique method.
Nesse H, 2015, [50]	Co-Cr restorations	Selective laser sintering (SLS)	Internal fit measuring with the replica method	SLS restorations had the worst internal and marginal fit comparing to casting and milling system.

Table 3 Studies evaluating 3D printed interim restorations

First author, year, [Ref.]	Printing technology	Evaluation method	Result
Lee WS, 2017, [53]	Polyjet method and stereolithography	Internal discrepancy measurement using the silicon replica method	The marginal and internal fit of the interim restoration has more outstanding 3D printing method than the CAD/CAM milling method.
Mai HN, 2017, [54]	Photopolymer-jetting 3D printing	To evaluate the fit of interim crowns using the image-superimposition and silicone-replica techniques	Photopolymer-jetting 3D printing significantly enhanced the fit of interim crowns, particularly in the occlusal region.
Alharbi N, 2018, [55]	Stereolithography	Scan of the mean gaps between the master die and interim restorations by micro-CT	3D printed interim restorations exhibit lower marginal and internal gaps than milled restorations.
Molinero-Mourelle P, 2018, [56]	Double jet printing (fused deposition modeling)	To measure the marginal fit	The marginal fit of 3D printed interim restorations was clinically acceptable.
Tahayeri A, 2018, [57]	Stereolithography	To evaluate the mechanical property	The results suggest that a 3D printable interim restorative material allows for sufficient mechanical properties for intraoral use.
Chaturvedi S, 2020, [58]	Stereolithography	To evaluate marginal and internal fit by measuring gaps using a scanning electron microscope	3D printed interim restorations have better marginal and internal fit compared to milled and molded interim restorations.

more accurate and had a greater retentive force than conventional denture bases. In 2019, the study examined the flexural bond strength between denture-based resins (heat cured one, milled one, and 3D-printed one) and commercially available denture teeth. In this study, teeth bonded to milling denture base and 3D-printed one showed significantly lower bond strength compared to a heat cured one [62].

Considering these results, it is thought that metal frameworks and denture bases can be used clinically on a research basis. However, issues remain with regard to the bonding of artificial teeth to denture bases made

with 3D printers. Additionally, it is necessary to verify the strength, deformation, and long-term prognosis of the tip in the undercut area of the clasp produced by 3D printers.

3D printing custom tray for manufacturing dental prosthesis

There have been a number of studies on verification of custom trays made with 3D printing. In a study that verified the accuracy of 3D-printed custom trays to obtain a precise impression of full-arch implant rehabilitation, it was reported that deviation in the position of the implant on the precision

cast was significantly less in the custom tray made by 3D printing [63]. Several studies have validated 3D-printed custom trays for totally edentulous cases [64,65]. In the literature searched in this review, 3D-printed custom trays for edentulous patients were reported to be better than conventional methods. In 2020, a study verified the adhesive strength of the impression material on 3D-printed custom trays. It concluded that polylactide tray materials may be recommended for the most severe impressions [66]. In conclusion, custom trays made by 3D printing are suitable for more precise impression taking than conventional custom trays, when considering that the adhesive strength of the impression material is maintained and the thickness of the impression material is uniform.

Discussion

There is no doubt that 3D printers will have a major impact on the dental field in the future. In this review, we looked at the prosthetic applications for 3D printers, but a limitation of this work is that many studies using 3D printers are not included. Many studies related to 3D printers remain to be validated. In the future, more detailed reviews will be needed in this area.

The following is a summary of this review of 3D printing: in the present circumstances, it is difficult to make a cast for a definitive prosthesis using a 3D printer; in relation to fabricating prostheses by 3D printer, it is considered the clinical application of cobalt-chromium is possible depending on the material and hardware of the 3D printer and that the clinical use of zirconia is difficult to assess. Further research is needed, such as verification of materials used, margin morphology, and hardware; clinically acceptable results have been reported for patterns using 3D printers, and if even better results are reported, general clinical application is considered possible; interim restorations made using a 3D printer have been reported with good results and are considered to be clinically usable; dentures made with 3D printers have a problem bonding between 3D-printed denture base and denture tooth, and need further verification in terms of strength and deformation; custom trays made with 3D printers are clinically useful, however, issues remain with design time and effort.

Conflict of interest

The authors declare no conflict of interest.

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