Clinical Applications of 3D-Printed Polymers in Dentistry: A Scoping Review

Evanthia Anadioti, DMD, MS
Private practice, Philadelphia, Pennsylvania, USA; Department of Preventive and Restorative Sciences, University of Pennsylvania School of Dental Medicine, Philadelphia, Pennsylvania, USA.

Teny Odaimi, BE, MS
University of Pennsylvania School of Dental Medicine, Philadelphia, Pennsylvania, USA.

Saoirse O'Toole, BA, BDent Sc, PhD
Department of Prosthodontics, Centre for Clinical, Oral and Translational Sciences, King's College London, London, England.

Purpose: The aim of this scoping review is to categorize 3D-printing applications of polymeric materials into those where there is evidence to support their clinical application and to list the clinical applications that require a greater evidence base or further development before adoption. ***Materials and Methods:*** An electronic search on PubMed, EMBASE, Scopus (Elsevier), and Cochrane Library databases was conducted, including articles written in English and published between January 2003 and September 2023. The search terms were: ((3D printing) OR (3-dimensional printing) OR (three dimensional printing) OR (additive manufacturing)) AND ((polymer) OR (resin)) AND (dent*). Case reports, in vitro, in situ, ex vivo, or clinical trials focused on applications of 3D printing with polymers in dentistry were included. Review articles, systematic reviews, and articles comparing material properties without investigation on clinical application and performance/accuracy were excluded. ***Results:*** The search provided 3,070 titles, and 969 were duplicates and removed. A total of 2,101 records were screened during the screening phase, and 1,628 records were excluded based on title/abstract. In the eligibility phase, of the 473 full-text articles assessed for eligibility, 254 articles were excluded. During the inclusion phase, a total of 219 studies were included in qualitative synthesis. ***Conclusions:*** There is lack of clinical evidence for the use of 3D-printing technologies in dentistry. Current evidence, when investigating clinical outcomes only, would indicate non-inferiority of 3D-printed polymeric materials for applications including diagnostic models, temporary prostheses, custom trays, and positioning/surgical guides/stents. *Int J Prosthodont 2024;37(suppl):s209–s219. doi: 10.11607/ijp.8829*

3D printing in dentistry is a rapidly moving and innovative field with ever-increasing applications. 3D printing is also called *additive manufacturing* (AM), where objects are produced layer by layer based on virtual 3D models. AM can generally be divided into seven process categories, with only four currently used in dentistry,[1] namely: *(1)* vat photopolymerization, which includes stereolithography (SLA), direct light processing (DLP), continuous DLP, and direct ultraviolet (UV) printing; *(2)* material extrusion, which includes fused deposition modeling (FDM) and fused filament fabrication (FFF); *(3)* material jetting; and *(4)* powder-bed fusion (PBF), which includes selective laser sintering (SLS) and direct-metal laser sintering. SLA is the most commonly used AM method in dentistry and involves laser polymerization of a UV-sensitive liquid monomer. The laser can work by curing from the top -down (in general, this tends to be more accurate and have a smoother finish) or bottom-up approach.[2] DLP uses light projection across the platform instead of a laser. FDM requires a heated extruder to melt thermoplastic polymer filaments,

Correspondence to:
Dr Eva Anadioti,
eva@welnoxstudio.com

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which then cool on the lowering printing platform.[2] SLS is the melting of polymer powder rolled onto the printing platform, then lowered with each layer that is printed.[2] PBF printing involves a printhead spraying liquid binder onto polymer powder to fuse layers, and the printing platform is lowered with each additional layer.[2]

Polymeric materials are considered one of the most utilized materials in dentistry, as their enhanced properties and versatility make them suitable for a wide range of applications across dental specialties. The most commonly used polymers in dentistry are polymethyl methacrylate (PMMA), polyurethane, polyethylene, polycarbonate, polyether ether ketone (PEEK), polyethylene glycol, polydimethylsiloxane, polylactic acid (PLA), poly(e-caprolactone), acrylonitrile butadiene styrene, and polypropylene.[3] Several of these polymers are being used with 3D printing for applications such as surgical guides, custom trays, working casts, and temporary restorations.[4] AM polymers are found in the form of thermoplastic filaments, reactive monomers, resin, or powder.

Although different types of printers have their relative advantages and disadvantages, it is important to recognize that the accuracy of the final printed product depends on the combination of the printing technology, the particular printer that is used, and the selected material.[5,6] Industrial printers have been reported to be superior to dental desktop printers,[5] and material jetting printers have been reported to be superior to SLA or DLP printers.[6] However, some of these may introduce a level of error that is not clinically relevant.

There is no comprehensive study comparing all printing technologies and available polymeric materials with milled and conventional prosthesis manufacturing. Given the rapid innovation in the field, the study design, products, and materials would most likely be improved during the time taken to complete and publish such a study. Given the constantly changing nature of the field, it is difficult to make evidence-based decisions on the appropriate use of these important tools and materials. Thus, the aim of this review is to categorize 3D-printing applications of polymeric materials into those where there is evidence to support their clinical application and to list the clinical applications that require a greater evidence base or further development prior to adoption.

MATERIALS AND METHODS

The scoping review protocol was registered on open science framework and can be viewed on the OSF website (osf.io/yajpv).

Research Question and Eligibility Criteria

This review was carried out around an exploratory research question regarding the clinical accuracy of 3D-printed materials, specifically polymer applications in dentistry. The central scoping review question was: "What is the available evidence on the suitability of use of 3D-printed polymers in clinical dentistry?" This central question was organized in a PICO format (Population, Intervention, Comparator, Outcome), with population being the test sample, intervention being the 3D-printed prosthesis, comparator being the standard of care method of manufacturing, and outcome being the measurement outcome (eg, trueness, precision, and marginal discrepancy).

The year of publication was limited to the last 20 years (2003 to 2023). The inclusion criteria were primary research articles consisting of in vitro, in situ, ex vivo, or clinical trials relating to applications of 3D-printed polymers in dentistry and case series relating to applications of 3D-printed polymers in dentistry with clinical outcomes. The exclusion criteria were articles not written in English, case reports, review articles or systematic reviews, and articles comparing physical properties of materials without investigating the clinical application performance/accuracy.

Sources of Information and Search Strategy:

A systematic bibliographic search was conducted through four databases: MEDLINE via PubMed, Scopus, Cochrane, and EMBASE. All searches were run up to October 29, 2023. For the search strategy, MeSH terms and free terms combined with the boolean operator OR within the same component were utilized. Then, the components were combined with the boolean operator AND.

The following terms were searched in each database: ((3D printing) OR (3-dimensional printing) OR (three dimensional printing) OR (additive manufacturing)) AND ((polymer) OR (resin)) AND (dent*). The asterisk represents a truncation function where the search term has a common root but multiple possible endings.

Articles were then imported into Zotero reference manager program (version 6.0.30) and duplicates were removed. Before starting the selection process, all reviewers were calibrated and obtained a Kappa coefficient of 0.95. The studies were searched and selected according to the eligibility criteria by calibrated reviewers (T.O. and S.O.), first by title and abstract and then by full text. In case of discrepancies, all three reviewers (T.O., S.O., and E.A.) reviewed the article.

Broadly, the applications could be listed under: study models and models for construction of definitive prostheses; surgical guides/stents; temporary prosthesis for indirect dentistry; occlusal appliances (guards and splints); orthodontic appliances; removable dental prostheses (complete and partial); definitive fixed prostheses; and dental implants. For each of these, the extraction table consisted of: author; year; type of article; study population; intervention (type of 3D printed prosthesis); comparator (type of conventional prosthesis); and outcome.

The extraction table was pilot-tested and refined after 10 articles. A broad synthesis of published studies following a narrative overview model was used to synthesize the evidence.

A PRISMA flow diagram was created to depict the flow of information processing through the different stages of the present systematic review. During the identification phase, a total of 3,070 records were identified from the following databases: MEDLINE via PubMed (n = 1,458), Cochrane (n = 133), Embase (n = 500), and Scopus (n = 979). No studies were manually identified, and 969 duplicate records were removed. A total of 2,101 records were screened during the screening phase, and 1,628 records were excluded based on title/abstract. In the eligibility phase, of the 473 full-text articles assessed for eligibility, 254 articles were excluded. In the inclusion phase, a total of 219 studies were included in qualitative synthesis (Fig 1). An Excel table that synthesizes all of the included studies was constructed. Key characteristics of each study were extracted in duplicate and independently. The evidence was grouped by type of clinical application.

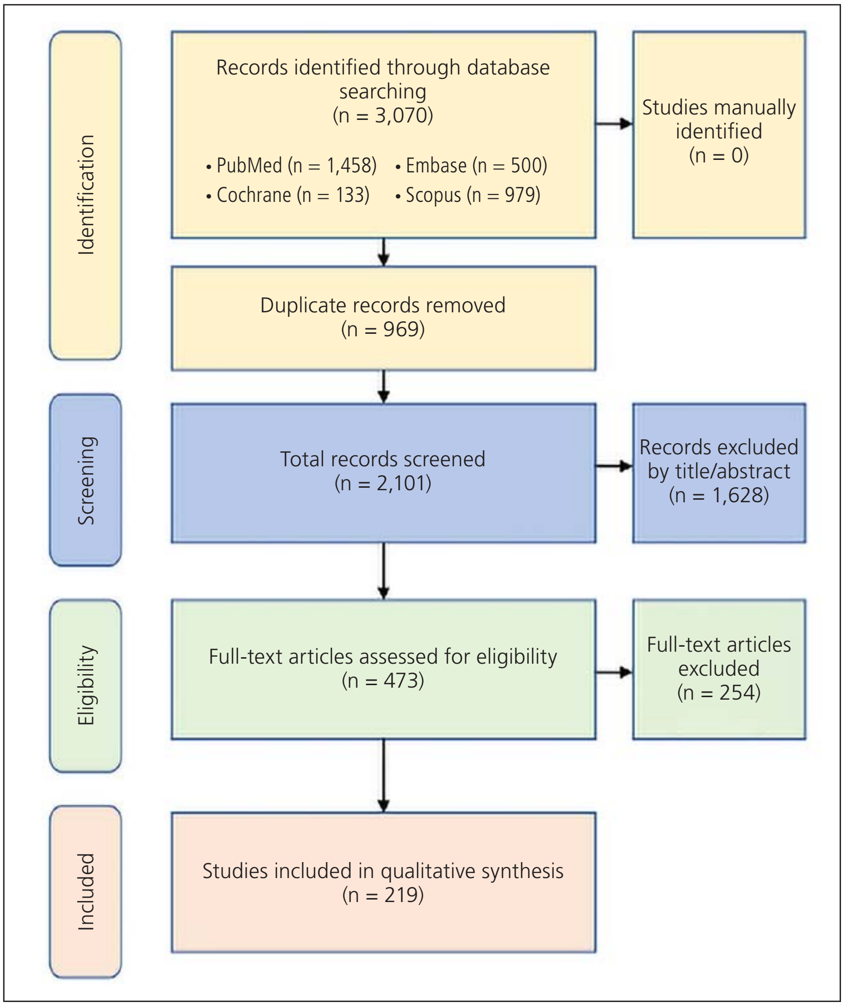

Fig 1 PRISMA flowchart of article selection for the systematic review.

RESULTS

Evidence-Based Clinical Applications of 3D-Printed Polymers

Study models and models for construction of definitive prostheses

Dental models have a variety of diagnostic, treatment-planning, laboratory, and chairside dentistry applications (Tables 1 and 2). Studies comparing conventional plaster casts, digital models, and 3D-printed SLA models demonstrated overall clinically acceptable accuracy for 3D-printed diagnostic models as a substitute for conventional stone casts.[7–9] Similarly, when comparing temporary resin crowns made on 3D-printed models to self-cured acrylic resin crowns, although a discrepancy was found, it was within clinically acceptable range (< 100 μm) and therefore acceptable.[10] However, when evaluating 3D-printed master casts where the accuracy required for definitive prosthesis is higher, the conventional methods of die fabrication still appeared superior to 3D printing.[11–13] Dental models for implant-supported prostheses require high accuracy and stability to ensure passive fit. Three studies comparing the accuracy of implant analog positions on complete edentulous maxillary casts fabricated from conventional dental stone vs AM with polymers found differences amongst the tested printers, printing technology, and implant analog systems used.[14–17] They all concluded that accuracy is clinically acceptable, depending on the combination used of the mentioned parameters. 3D-printed models are used in oral and maxillofacial surgeries for treatment-planning and surgical preparation purposes with acceptable accuracy of the maxillofacial structures compared to conventional methods.[18,19]

Although there are no clinical studies, there is overall adequate available evidence for the utilization of 3D-printed resin models in fabricating diagnostic models with acceptable clinical accuracy. The accuracy is dependent

Table 1 Clinical Applications of 3D-Printed Polymers with Sufficient Evidence to Be Considered Standard of Care

Application	Evidence
Models	3D-printed resin models for diagnostic model fabrication could be considered as accurate as standard of care. Models for definitive restorations require additional evidence.
Temporary prostheses	3D-printed temporary prostheses could potentially become standard clinical practice due to decreased manufacturing time, predictability with digital planning, and reduced cost compared to conventional lab-made long-term temporary prostheses.
Surgical guides/ positioning stents	Surgical guides or positioning stents are a clinical application whereby 3D-printed guides can be considered standard of care. There was agreement in every study that 3D-printed surgical guides were not significantly different to milled or thermoplastic guides despite a range of 3D-printing techniques and materials being used and offered many advantages, including less waste compared to subtractive techniques and less laboratory time. Overall, a range of innovative guides can be observed in the literature, ranging from endodontic guides for access and post removal to tooth preparation guides.
Custom trays	3D-printed custom trays have sufficient clinical evidence to be considered standard of care and have reduced fabrication times and costs compared to conventional care.

Accuracy is dependent on many factors, including but not limited to: the printer used, printing technology, material, printing parameters, build angle, postprocessing procedures, 3D-printing manufacturing method, 3D-printing material, printing interval, and more.

Table 2 Clinical Applications of 3D-Printed Polymers Requiring Further Evidence

Application	Evidence
Occlusal appliances	There is insufficient clinical data to be considered standard of care compared to cold-cure acrylic or milled devices. In vitro studies have observed both to be suitable for clinical use, and short-term trials observed no statistical differences between 3D-printed splints and conventional splints regarding patient satisfaction, complication rates, and wear behavior after 3 months. Long-term data are needed to determine the impact of inferior physical properties.
Definitive restorations	Most studies conclude that although conventional wax or milled wax is statistically more accurate, 3D-printed restorations are within a clinically acceptable range. There are no studies to date demonstrating longevity.
Orthodontics	3D-printed trays for indirect bonding of brackets have been observed to be less accurate but clinically acceptable compared to traditional PVS trays. While it is becoming more common to print aligners, the evidence for clinical use is lacking.
Complete removable dental prostheses	The available evidence shows that 3D-printed dentures exhibit similar adaptation and retention to the milled or conventionally fabricated ones. There are no long-term data on material longevity or biofilms created after a substantial intraoral period. More evidence is needed before they can be considered standard of care.
Partial removable dental prostheses	Conflicting results were observed on the accuracy of SLS-fabricated rests, proximal plates, connectors, and clasp arms. Further work is required in this field.

Accuracy is dependent on many factors, including but not limited to: the printer used, printing technology, material, printing parameters, build angle, postprocessing procedures, 3D-printing manufacturing method, 3D-printing material, printing interval, and more.

on many factors, including but not limited to the printer used, printing technology, material, printing parameters, build angle, postprocessing procedures, and more. Models for definitive restorations require additional evidence.

Temporary prostheses

No clinical trials assessing the fit and integrity of 3D-printed temporary prostheses were found in the search. Three in vitro studies investigated the trueness[20] and marginal deviation[21–23] of 3D-printed temporary prostheses compared to milled or conventionally molded temporary prostheses. No studies have reported precision. All studies have reported the 3D-printed temporary prosthesis to be sufficient for clinical use. One early in vitro study[20] investigated the accuracy of printing commercial resins in simple blocks using SLA 3D printers compared to conventionally cured and commonly used provisional materials. They observed that 3D printing could result in up to 22% dimensional error but concluded it was sufficient for intraoral use.[20] A more clinically relevant investigation of different AM methods on three-unit fixed dental prostheses observed all prostheses to be acceptable, with AM restorations having decreased accuracy compared to milled restorations but superior accuracy compared to manual prostheses.[21] Unsurprisingly, printing at 100-μm intervals was less accurate than printing at 50-μm. Another in vitro study investigated the use of different 3D-printed materials to make temporary prostheses and observed marginal discrepancies of 316.5 ± 34 μm with an epoxy resin–based polymer and of 205 ± 51.25 μm with a urethane dimethacrylate–based polymer,[23] both of which could potentially be classified as clinically unacceptable, given that

Fig 2 3D-printed bone reduction and implant surgical guide.

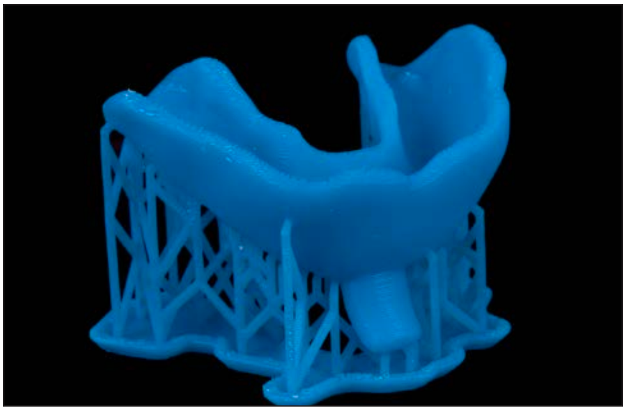

Fig 3 3D-printed custom tray with supports.

120 µm is often quoted as a clinically acceptable marginal discrepancy after cementation.[24] The milled group was observed to have a 93 ± 11.75–µm discrepancy. In contrast, one in vitro investigation using polymer jetting observed that the 3D-printed group had the lowest marginal discrepancy (99 ± 19 µm) compared to milled groups (125 ± 30 µm).[22]

3D-printed temporary prostheses could potentially become standard clinical practice due to decreased manufacturing time, predictability with digital planning, and reduced cost compared to conventional lab-made long-term temporary prostheses. The data suggest that 3D-printed temporary restorations can offer clinically acceptable fits but are influenced by 3D-printing manufacturing method, 3D-printing material, and printing interval (50 vs 100 µm).

Surgical guides/positioning stents

Six studies reported data comparing 3D-printed surgical guides and milled or thermoplastic guides for implant placement[25–29] and one for bone augmentation.[30] There was agreement in every study that 3D-printed surgical guides were not significantly different to milled or thermoplastic guides despite a range of 3D-printing techniques and materials being used and offering many advantages, including less waste compared to subtractive techniques and less laboratory time. One in vitro study observed differences between printer, polymer, and the sterilization technique used.[31] However, despite the noted differences in accuracy, all guides resulted in clinically acceptable implant placement in the patient replicas. There was one contradictory study that examined the use of an occlusal positioning stent for maxillofacial surgery and observed that the mean absolute error of a 3D-printed device compared to a standard cold-cure appliance was 0.94 ± 0.09 mm (range: 0.04 to 1.73 mm).[32] Although the study was published in 2014 and both scanners and 3D printers are likely to have improved since then, the upper end of this range would be considered too great an error for clinical use. Overall, a range of innovative guides can be observed in the literature, ranging from endodontic guides for access[33] and post removal[34] to tooth-preparation guides.[35,36] The use of 3D-printed guides for injection molding has also been reported several times as case reports.[37]

Surgical guides or positioning stents are a clinical application whereby 3D-printed guides can be considered standard of care (Fig 2).

Custom trays

As custom trays have traditionally been made with different polymers, it is one of the applications that has been affected by 3D printing (Fig 3). However, only two studies by the same authors were found to investigate their accuracy compared to the conventional technique. The authors first conducted an in vitro study comparing FDM 3D-printed trays to PMMA conventional ones.[38] After digitization of the impressions, the 3D-printed trays had more accurate implant positions than the conventional ones. In their subsequent clinical study, with regards to impression accuracy, clinical tray fit, impression quality, and cast quality, no statistically significant difference was found between test and control groups ($P > .05$).[39] When examining the fabrication time and cost, the 3D-printed group was superior to the control group. AM-made custom trays appear to have sufficient evidence to be adopted as a standard of care in clinical practice.

Clinical Applications of 3D-Printed Polymers Requiring Evidence

Partial removable dental prostheses

Three studies were reviewed on partial dentures fabrication where either a 3D-printed resin pattern that was then cast was used or a directly 3D-printed metal

Fig 4 3D-printed maxillary and mandibular complete removable dental prostheses.

framework using selective SLS was used. One of the studies found no significant differences ($P > .05$) in the mean ± SD of the overall fit of cast metal frameworks made from conventionally waxed patterns to ones that were made from 3D-printed resin patterns.[40] On the other hand, Tasaka et al compared the accuracy of the different removable partial denture components on frameworks fabricated by 3D-printed pattern-casting compared to those fabricated by SLS.[41,42] The authors observed statistically significant differences at the rests, proximal plates, connectors, and clasp arms, with the SLS having smaller gaps.

Complete removable dental prostheses

Two clinical crossover studies were found that compared clinical parameters of 3D-printed complete removable dental prostheses (CRDPs), such as adaptation, retention, and occlusal forces. One study found no significant differences for adaptation or retention between the conventional and 3D-printed dentures,[43] while the second study found differences in the occlusal schemes, with the printed one having less favorable distribution.[44]

An important potential benefit of a CAD/CAM denture base is the ability to decrease the thickness while maintaining clinically acceptable mechanical properties. One study showed that while the heat-polymerized and milled resins showed no significant difference down to a minimum thickness of 1.5 mm, the printed resins were statistically significantly different and recommended a 2-mm minimum thickness for clinically acceptable mechanical properties.[45] A recent study compared the accuracy of milled vs printed complete denture bases and teeth as well as the position of the teeth on the corresponding denture bases.[46] Although a higher denture base accuracy was found for milled bases, the denture teeth position was more accurate for the printed group. Similar results were found when printed denture teeth position was compared to conventional mandibular dentures, but the authors interestingly reported a significant difference in position on maxillary dentures.[47] One in vitro study compared the accuracy and trueness of different denture teeth polymers printed with different printers.[48] As expected, significant differences were observed amongst the combinations of printer and material. Printing parameters and postpolymerization conditions affect the accuracy of the printed prosthesis.[49] An in vitro study evaluated the trueness and fit accuracy of the tissue surface of maxillary complete dentures (CDs) manufactured using milling and 3D printing technology as compared to conventional fabrication.[50] The milling technique demonstrated the highest trueness and fit accuracy in all regions among the three manufacturing methods, and the SLA printer showed the highest fit accuracy among all 3D printers, specifically at an angle of 45 degrees, where it was even slightly higher than that of a conventionally fabricated CD base.[50] Similarly, another study evaluated the trueness of the printing materials, using three layer thicknesses (50, 75, and 100 µm), two build angles (0 and 45 degrees), and three plate locations (side, middle, and corner).[51] Optimal results were again found using the 45-degree angle, and layer thickness was a primary parameter in determining accuracy among all, while higher discrepancies and failures were observed in 0-degree prints.[51] Lastly, one in vitro study evaluated the effect on trueness and precision when the number of supports was reduced while printing a CD.[52] Although the control performed best, the distribution area revealed that the differences may not be clinically relevant. The authors concluded that reducing the supports may be beneficial to maintain printing accuracy while reducing time and resin consumption.

There are very limited clinical studies and no long-term data available on the performance of these 3D-printed denture polymers (Fig 4). The available evidence shows that 3D-printed CRDPs exhibit similar adaptation and retention to the milled or conventionally fabricated ones. Taking into consideration the reductions in cost and time, this clinical application seems to be predominantly used with AM in the near future, but more evidence is needed.

Occlusal appliances

There were two studies that assessed clinical outcomes associated with occlusal appliances to manage bruxism and temporomandibular disorders (TMDs). One clinical trial compared the use of 3D-printed and milled oral appliances with a 3-month follow-up period for the treatment of bruxism and TMDs.[53] After 3 months, there were no statistical differences between the two groups regarding patient satisfaction, complication rates, and wear behavior. However, that was a pilot study and was underpowered to assess clinical change. Adequately powered long-term use needs to be assessed. An in vitro study[54] investigated the accuracy of 3D-printed vs milled bite splints and observed that both devices were suitably accurate, with the milled devices demonstrating higher trueness and the 3D-printed devices having greater precision. The authors reported that both manufacturing methods were suitably accurate for clinical use.[54]

When comparing physical properties, in vitro material studies demonstrate that 3D-printing materials have inferior physical properties compared to their milled or conventionally constructed counterparts, including reduced flexural strength,[55] higher eluent release,[56] and reduced wear and fracture resistances,[57] particularly after sustained immersion in water.[58] Overall, there is not sufficient long-term data to say that 3D-printed occlusal devices can be considered standard of care compared to cold-cure acrylic or milled devices.

Definitive restorations

A single randomized controlled trial on pediatric patients reported that 3D-printed resin crowns provide superior gingival health and better marginal integrity compared to direct composite crowns, though the retention was lower after 1 year.[59]

Six in vitro studies evaluated the accuracy of 3D-printed resin copings or patterns to be invested or pressed into definitive restorations. Although the AM process is not directly used to fabricate the definitive restoration, it is used as part of the process, and its accuracy is worth reviewing. Most of the results conclude that although conventional or milled wax is statistically more accurate, the 3D-printed wax is within the clinically acceptable range and thus the clinical differences may be negligible.[60–63] One study concluded that 3D-printed copings were superior to milled ones,[64] but another study found that the printer was unable to produce a uniform internal gap of the copings.[65] Lastly, one study found that the number of copings being printed at the same time affected the fit.[66]

In a similar study, Piangsuk et al compared the accuracy of post and cores created with three different fabricating techniques: direct conventional, machine milling, and 3D printing.[67] The accuracy of the 3D-printed resin pattern (26.89 ± 11.09 mm^3) was found to be inferior compared to the milled resin pattern (28.20 ± 11.41 mm^3; $P = .0002$); however, the final adjusted metal post and core fabricated with three different techniques showed no statistical difference in accuracy ($P = .15$). The same authors also compared the accuracy of reinforced printed wax and castable resin and found that both showed a volume reduction from the original file.[68] Three in vitro studies compared the accuracy of 3D-printed composite resin fixed single prostheses, such as crowns or inlays, to milled ones. Two studies showed superior overall fit and marginal fit for DLP 3D-printed crowns[69] and inlays,[70] respectively. The third study found no difference in the linear measurements but did find smaller 3D deviations for the milled crowns,[71] but it is important to note that that study used a low-cost LCD (liquid crystal display) 3D printer that is not commonly used in clinical dental practices.

A new category of polymer material used in permanent fixed restorations is a hybrid that includes a resin base with ceramic particles. Hybrid materials have been developed and used with subtractive manufacturing and are now becoming available in AM as well. One in vitro study evaluated the marginal adaptation and fracture resistance of a milled hybrid nanoceramic (Cerasmart), ceramic-filled hybrid 3D-printed material (Varseosmile), and a polymer-infiltrated ceramic network (Vita Enamic) with different occlusal thicknesses.[72] The 3D-printing technique provided superior marginal adaptation over the milling ones. However, the mechanical properties of the 3D-printing material need further advancement, as the printed hybrid crowns fractured at the lowest loading force (1,480.3 ± 226.1 N).

While polymers may have limited applications for definitive fixed restorations, they are an integral part of the fabrication process. The accuracy of each step of the process ensures the final fit of the restoration and its long-term success. The current evidence suggests that 3D-printed polymers perform well in the manufacturing process of definitive restorations, but long-term clinical studies are needed to demonstrate the strength and periodontal response when used as long-term restoration.

Orthodontics

Two studies evaluated the accuracy of polymer trays for indirect bonding of brackets, one using DLP and the other an SLA printer, compared to traditional polyvinyl siloxane (PVS) trays.[73,74] Both concluded that the PVS trays were more accurate, but the printed ones were within the clinically acceptable range. A study compared the thickness of 3D-printed aligners with two different resins to the digital design file.[75] The authors found that both trays had increased thickness compared to the digital file and that there was a difference between the two resins, with one considered clinically unacceptable. A study compared 3D-printed PLA material as a permanent retainer on mandibular anterior teeth and found comparable retention and color stability when measured against the metal retainers.[76] While it is becoming more common to print aligners, the evidence for clinical use is lacking.

Future Applications of 3D-Printed Polymers: Implants

Implants are used in dentistry to replace missing teeth or restore facial deformities. While those traditionally have been metal (predominately titanium) or even ceramic, polymers have also been used to fabricate patient-specific implants. One experimental study on 3D printing custom implants using PEEK in an FFF printer[77] reported high strength values, even after artificial aging. Case reports on custom facial implants made of PEEK[78] or PMMA[79] have been reported in orthognathic and maxillofacial surgery with favorable short-term results. There is no clinical evidence on 3D-printed implants, but with the limited evidence on facial implants and the continuous advancement of printed polymers, this clinical application could emerge in the future.

DISCUSSION

The purpose of the scoping review was to report the available evidence of the clinical applications of dental polymers. Polymeric materials are currently the most common option for 3D printing in dentistry. While several printable polymers have been developed, there are still drawbacks that limit their clinical applications. As with any new technology, the first research studies are focused on material properties rather than clinical parameters. This review aimed to identify the clinical evidence for polymers in dentistry, and therefore all studies evaluating primarily material properties were excluded.

There is a general lack of clinical evidence for utilization of 3D printing in dentistry. From the available research reviewed, only diagnostic models, surgical guides, custom trays, and temporary restorations appear to have a level of evidence that currently supports their clinical implementation. These applications generally allow for a higher margin of error due to the short-term use and appear to be logical applications for the initial phase of new technology.

Known clinical applications of polymers, such as removable prostheses and occlusal splints, are greatly lacking evidence to support their use. There are studies focused on mechanical properties (such as impact strength,[80] denture teeth wear resistance,[81–83] water sorption,[84] and the bond strength between teeth and denture base[85–87]) that show promising short-term results, but those did not report any clinical parameters, and therefore they were excluded from the present review. Previous reviews agree with the results of a study[88] that reported that 3D printing in removable prosthodontics is recommended for interim prostheses, custom trays, or record bases.

A recurrent theme across applications was that 3D-printed polymers were less accurate than their conventionally made or milled counterparts but were still within a clinically acceptable range. This perhaps leaves a wide range for clinician-led decisions whereby a 3D-printed prosthesis may be applicable in some cases and not others, depending on the level of accuracy needed and the financial parameters.

The present review has several limitations. Although a systematic search was applied in four different databases, it is possible that some publications wre missed. Secondly, this review is limited by the lack of clinical data to infer clinical outcomes. However, it has been clearly highlighted throughout the review when clinical data was available for review. The scope of this paper was broad. Again, this reflects the lack of data to singly investigate any of the individual clinical applications. When more evidence becomes available, hopefully a more detailed review is possible, perhaps with a meta-analysis of data. A final, large limitation is the lack of standardization in the method of measuring the accuracy between different clinical applications in dentistry. The digital nature of 3D printing often encourages a digital method of assessment, wherein scans of the prosthesis are superimposed and the root mean square deviation between the two meshes is used to assess differences. However, comparisons across different types of data are invalid, as the measure is dependent on the scale of the difference. Furthermore, as the mathematical computation of difference involves squaring values, a large error will have a disproportionately large effect, making it highly sensitive to outliers.

A more useful clinical tool would be to accurately register the two scans and present areas of greatest deviation while assessing whether these deviations fit within a clinically acceptable tolerance range. The level of precision (ie, repeatability of the measure) should also be assessed. Clinical parameters of assessment are also needed, and assessments should not rely on ex vivo digital assessment alone.

CONCLUSIONS

This scoping review highlights the lack of clinical evidence for the use of 3D-printing technologies, specifically evidence with long-term clinical data. The current evidence, when investigating only clinical outcomes, indicates a non-inferiority of 3D-printed polymeric materials for applications (diagnostic models, temporary prostheses, custom trays, and positioning/surgical guides/stents). However, due to reduced physical properties and an increased risk for clinical degradation, long-term clinical data is needed before 3D-printed devices can be recommended as anything other than a short-term prosthesis.

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