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Review Article

# 3D printing in dental prosthetics and implants: Current and emerging applications

**Manjiri Chakor[1], Zaid Sakarna[2]*, Sabrina de Carvalho Sakane[3], Mummana Sasi Priyanka[4], Marina Adly Kaldas Bekheit[5], Jayeesha Kothapalle[6], Sandeep Singh[7]**

[1]Dept. of Oral and Maxillofacial Surgery, RD Dental College and Research Center, Nagpur, Maharashtra, India
[2]Dept. of General Dentistry, Uzhhorod National University, Zakarpattia Oblast, Ukraine
[3]Dept. of Endodontics, Brazilian Dental Association, Curitiba, Brazil
[4]Dept. of General Dentistry, Sree Sai Dental College and Research Institute, Srikakulam, Andhra Pradesh, India
[5]Dept. of Oral and Maxillafacial Radiology, Faculty of dentistry, Ain Shams University, Cairo, Egypt
[6]Dept. of General Dentistry, AECS Maaruti Dental College and Research Centre, Bengaluru, Karnataka, India
[7]Dept. of Prosthodontist, Post Graduate Institute of Dental Sciences, Rohtak, Haryana, India

## Abstract

Three-dimensional (3D) printing is revolutionizing prosthodontics by enabling highly precise, efficient, and customizable fabrication of dental restorations and devices. This additive manufacturing technology supports the production of a wide range of prostheses including crowns, bridges, removable and fixed dentures, implant frameworks, surgical guides, and maxillofacial prostheses by building structures layer by layer with exceptional accuracy. 3D printing streamlines digital workflows by integrating advanced CAD/CAM design, diverse biocompatible materials, and rapid prototyping techniques, resulting in reduced manual errors and improved clinical outcomes. Despite significant advantages such as enhanced fit, reduced fabrication time, and personalized treatment, challenges persist, including high initial costs, material property limitations, and the need for standardized protocols and rigorous clinical validation. Ongoing innovations in materials, printing technologies, and interdisciplinary collaboration promise to expand the scope and effectiveness of 3D printing in prosthodontics. This review comprehensively explores the current applications, advantages, limitations, and future directions of 3D printing in dental and maxillofacial prosthetic rehabilitation, positioning it as a transformative force in modern digital dentistry.

**Keywords:** Digital dentistry, CAD/CAM, Additive manufacturing, Dental implants, Prosthodontics, Dental prosthesis, 3d Printing, Digital denture.

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## 1. Introduction

The advent of digital technology has brought about a paradigm shift in modern dentistry, reshaping conventional treatment workflows and enhancing interdisciplinary collaboration among clinicians, surgeons, and dental technicians. In prosthodontics, particularly, digitalization has become a cornerstone, influencing every stage of care, from radiographic diagnostics and digital impression techniques to virtual jaw relation recording and the computer-aided design and manufacturing (CAD/CAM) of fixed and removable prostheses. These advancements have streamlined clinical procedures, improved treatment outcomes, and elevated patient satisfaction. As digital dentistry continues to evolve, it is increasingly being embraced by practitioners for its precision, efficiency, and ability to deliver highly customized prosthodontic solutions.[1]

Over the years, two primary manufacturing approaches, subtractive and additive, have emerged to transition digital designs created through Computer-Aided Design (CAD) into tangible objects via Computer-Aided Manufacturing (CAM). Subtractive manufacturing, often referred to as milling, employs computer numerical control (CNC) machines to carve dental components from solid blocks of material through cutting and drilling. In contrast, additive manufacturing (AM), commonly known as three-dimensional (3D) printing or rapid prototyping, fabricates

*Corresponding author: Zaid Sakarna
Email: drsandeepsingh011@gmail.com

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objects by depositing material layer by layer, typically through the sintering of powders or polymerisation of resins guided by digital blueprints.[2] Since its initial patent in 1986 by Charles Hull, 3D printing has steadily gained traction in dentistry, particularly since the early 2000s. Its ability to produce intricate geometries, minimise material waste, and streamline fabrication has made it a compelling alternative to traditional subtractive techniques.[3]

In the field of implant-supported prosthetic rehabilitation, 3D printing has been employed for several years to enhance the precision and efficiency of treatment. Metal frameworks, particularly those fabricated from titanium or cobalt–chromium alloys, can now be produced with accuracy comparable to that of conventionally manufactured components, although they often require post-processing through milling for optimal fit and finish.[4] While much of the initial focus in additive manufacturing has been on polymer-based superstructures, recent advancements in technology and material science have paved the way for novel applications. Emerging options such as printable ceramics and hybrid materials show promising potential but warrant thorough evaluation before routine clinical use.[5] Additionally, 3D printing plays a vital role in the fabrication of surgical guides, offering high precision and customisation for implant placement.[6] This review article aims to explore the current and emerging applications of 3D printing in prosthodontics, particularly in the design and fabrication of dental prostheses and implant-supported restorations, while highlighting the advantages, limitations, and future directions of this transformative technology.

## 2. Methodology

This narrative review was conducted to explore the current and emerging applications of three-dimensional (3D) printing in dental prosthetics and implantology. A non-systematic, comprehensive search of the literature was performed across multiple electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar, for articles published up to June 2024.

### *2.1. Search strategy*

Keywords used in the search included: “3D printing,” “additive manufacturing,” “digital dentures,” “prosthodontics,” “dental implants,” “CAD/CAM,” “stereolithography,” “maxillofacial prosthesis,” and “dental materials.” Boolean operators (AND/OR) were employed to refine search results and capture relevant studies.

### *2.2. Inclusion and exclusion criteria*

1. Included studies met the following criteria:
    a. Peer-reviewed journal articles, review papers, and relevant in vitro or clinical studies.
    b. Topics related to the use of 3D printing in fixed or removable prosthodontics, implantology, or maxillofacial rehabilitation.
    c. English-language publications.
2. Excluded were:
    a. Non-dental applications of 3D printing.
    b. Articles without full text or methodological detail.
    c. Editorials, commentaries, and non-peer-reviewed sources.

### *2.3. Data extraction*

Relevant literature was reviewed, and data were categorized according to the type of 3D printing technology, material used, clinical application, and reported advantages or limitations. The findings were synthesized under thematic subheadings to provide a comprehensive understanding of the current trends and future directions of 3D printing in prosthodontics.

## 3. 3D-Printing Methods

### *3.1. Selective laser sintering (SLS)*

SLS is a 3D printing technology used in dentistry to fabricate dental frameworks and bases. It involves using a high-powered laser to selectively fuse fine layers of powdered material, building the object layer by layer. Originally developed at the University of Texas, this technique produces highly detailed and accurate models with natural contours, making it ideal for managing complex dental cases. One of its key advantages is its high resolution, up to approximately 60 microns. However, drawbacks include the potential inhalation hazard from fine particles, difficulty in managing excess powder, and slower production speeds compared to some other 3D printing techniques.[7]

### *3.2. Fused deposition modeling (FDM)*

FDM has gained popularity in prosthodontics due to its affordability, accessibility, and versatility. It is particularly useful for fabricating diagnostic models, surgical guides, and orthodontic appliances. For example, FDM-produced surgical guides have shown enhanced accuracy and efficiency in implant placement, contributing to reduced surgical time and improved patient outcomes. Similarly, orthodontic models produced using FDM offer precise representations of dental arches, aiding in treatment planning and appliance fabrication.[8]

Developed by Scott Crump, FDM operates by heating thermoplastic filament and extruding it through a temperature-controlled nozzle. The material hardens almost immediately after extrusion, allowing layer-by-layer construction of the object. The process is managed by a processor that regulates both temperature and material distribution. Common materials used in FDM include acrylonitrile butadiene styrene (ABS), polysulfones, and polycarbonates. FDM’s rapid prototyping capabilities support iterative design and testing, significantly speeding up the development of dental devices.[7]

### 3.3. Stereolithography (SLA)

SLA, one of the earliest 3D printing technologies, was developed by Charles Hull in 1984. It uses a photosensitive liquid resin that is cured layer by layer with a UV laser. As each layer is cured, it bonds to the previous one, gradually forming a solid 3D object. SLA is widely used in prosthodontics for fabricating precise and customized dental prostheses such as crowns and bridges. Its ability to produce highly detailed structures with intricate geometries has made it a preferred alternative to traditional fabrication techniques. Additionally, SLA is extensively applied in orthodontics for manufacturing clear aligners and other orthodontic appliances, owing to its accuracy and fine surface finish.[9,10]

### 3.4. Digital light processing (DLP)

DLP is a fast and efficient 3D printing technology commonly used in dentistry, especially for fabricating dental restorations and orthodontic models. Like SLA, DLP uses a light source to cure a photosensitive resin. However, instead of curing resin point by point, DLP cures entire layers simultaneously, significantly speeding up the printing process. This technology enhances the mechanical and antibacterial properties of polymethyl methacrylate (PMMA) composites, making it well-suited for dental applications. However, its use is limited to photopolymer resins, which may emit unpleasant odors, making them less ideal for some clinical or office environments.[11]

### 3.5. Direct metal laser sintering (DMLS)

DMLS is a high-precision 3D printing technology that uses powerful lasers to selectively fuse fine metal powder, layer by layer, to form solid metal restorations. Commonly used materials include cobalt-chromium and titanium, making DMLS ideal for producing durable dental prostheses, such as crowns, bridges, and implant components. This method offers superior fit and mechanical strength compared to traditional casting techniques. However, the high cost of equipment and materials remains a significant limitation in its widespread adoption in dental practices.[12]

### 3.6. Material jetting

It is an advanced additive manufacturing process where droplets of liquid material are selectively deposited and cured layer by layer to build complex dental restorations. It offers exceptional accuracy, surface quality, and the ability to print with multiple materials simultaneously. In prosthodontics, this technique is particularly useful for creating highly detailed and biocompatible models, including temporary crowns, veneers, and implant guides. Common materials include photocurable resins for fine detailing, ceramics for their esthetics and biocompatibility, and metal alloys for strength and longevity. Material jetting significantly improves the speed and precision of restoration fabrication, enabling faster design iterations and better clinical outcomes.[13,14]

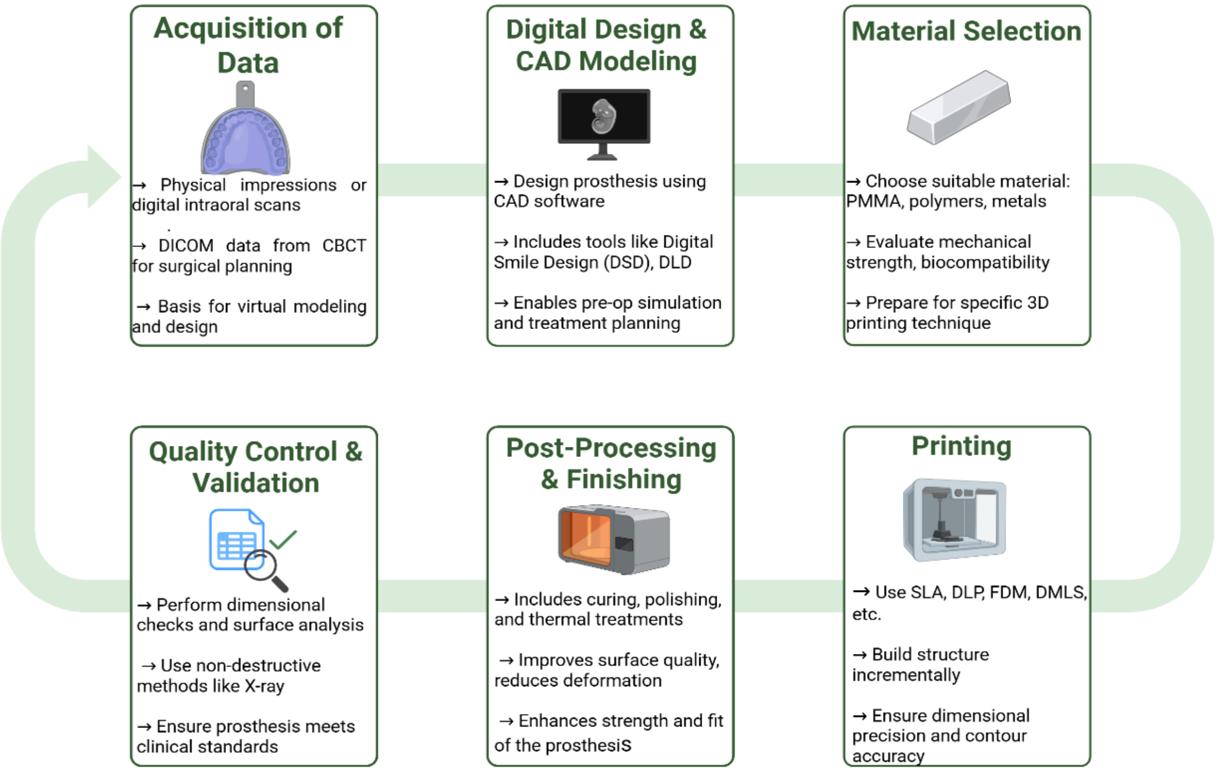


**Figure 1:** Mechanism of action of 3d printing

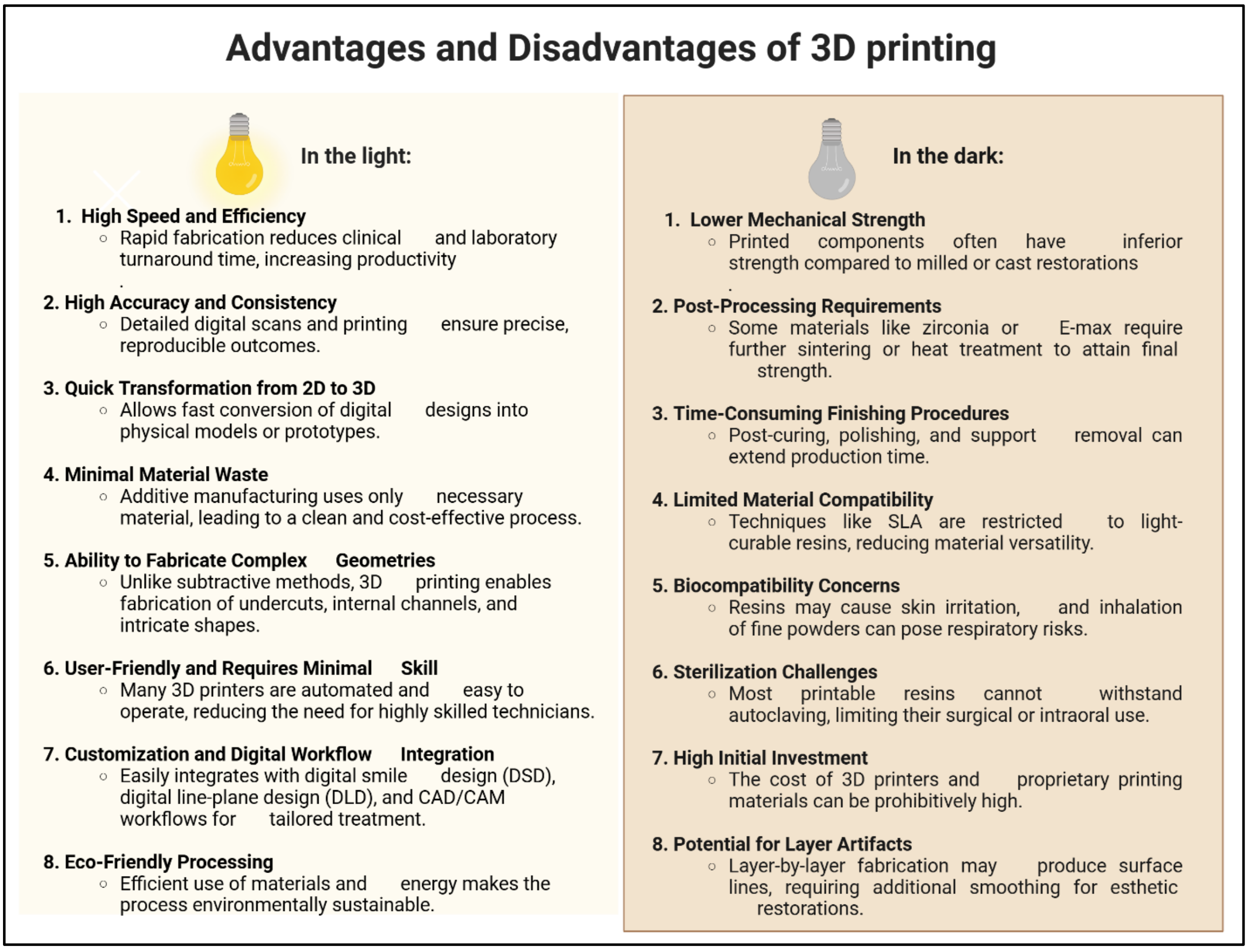


**Figure 2:** Advantages and disadvantages of 3D printing[16]

**Table 1:** 3D printing materials[15-16]

| Material Type | Clinical Application | Characteristic |
|---|---|---|
| Photopolymer Resins | Crowns, bridges, temporary prostheses, aligners | High-resolution, smooth surface finish, Higher printing temperatures (70°C) improve double bond conversion and mechanical strength. |
| Metal Alloys (Co-Cr) | Implant-supported frameworks, partial dentures | High strength, corrosion resistance; Selective Laser Melting (SLM) yields clinically acceptable discrepancies with z-axis showing the least distortion. |
| Polyether Ether Ketone (PEEK) | TMJ devices, removable partial dentures | Excellent wear resistance, lightweight; 3D-printed prosthesis |
| Polylactic Acid (PLA) | Temporary crowns, bridges, ortho appliances | Biodegradable, easy to print; FDM-printed crowns were successful in multiple cases with good adaptation. Limitations: surface roughness, thermal degradation. |
| Polyvinyl Alcohol (PVA) | Support structures, casting/molding models | Water-soluble, dissolvable; Chairside provisional crowns on PVA-printed models showed accurate fit and were efficient to fabricate. |
| Thermoplastic Elastomers | Soft liners, bite guards, occlusal splints | Flexible, impact resistant; Force and moment delivery varied by material and rotation direction, impacting aligner biomechanics. |
| Hybrid Composites | Hybrid dentures, implant prostheses, orthodontic corrections | Customizable aesthetics; Used in direct restorations to reshape teeth post-orthodontics, enhance smile design, and maintain gingival health. |

### *3.7. Mechanism of action of 3d printing*

The digital printing workflow in prosthodontics involves several essential steps that begin with the acquisition of patient data, either through physical impressions or digital methods such as intraoral scanning and DICOM imaging. This is followed by digital design and CAD modeling, which employ advanced tools like Digital Smile Design (DSD) and digital line-plane design (DLD) for accurate planning and customization of oral and maxillofacial prostheses. CAD/CAM technologies further enhance treatment outcomes in prosthodontics and orthodontics by enabling virtual simulations, appliance design, and clear aligner fabrication. Material selection and preparation are critical, involving biocompatible materials such as PMMA, metal powders (e.g., Cr, Mo, Ag), and polymeric systems, all chosen based on their mechanical and biological properties. The printing process uses rapid prototyping techniques like SLA, DLP, and fused deposition modeling to fabricate detailed prostheses layer by layer, with accuracy influenced by parameters like layer thickness. Post-processing techniques such as photopolymer curing and thermomechanical treatment improve the strength, dimensional stability, and surface quality of the printed prostheses. Finally, quality control ensures the clinical acceptability of the prostheses through dimensional measurement, surface roughness analysis, and non-destructive testing methods such as X-ray or ultrasound to confirm internal integrity without damaging the final product (**Figure 1**).[15]

### *3.8. Applications of 3D printing in prosthodontics*

#### *3.8.1. Application of 3D printing in removable prosthodontics*

#### *3.8.2. Complete dentures (CDs)*

CDs restore function and aesthetics in patients who have lost all natural teeth. Recent advancements in digital dentistry, particularly CAD-CAM milling and 3D printing, have introduced alternative methods for fabricating CDs. While digital dentures often demonstrate acceptable adaptation and occlusal accuracy, occasionally surpassing conventional dentures, certain limitations, such as inaccuracies at the posterior palatal seal and peripheral borders, remain. Denture precision is influenced by multiple factors, including fabrication technique, CAD-CAM parameters, and analytical methods. One clinical study by Emera et al, evaluated the fit and retention of 3D-printed dentures using dimethacrylate-based resins in comparison to conventional dentures in ten edentulous patients. Each patient received both types, and assessments were done using surface-matching software and digital force meters at insertion, 3 months, and 6 months. The study found no significant differences in base adaptation or retention between the two types. These findings suggest that 3D-printed dentures can be a clinically acceptable alternative to conventional ones.[17,18]

#### *3.8.3. Removable partial dentures (RPDs)*

3D printing technology has extended its applications to the fabrication of removable partial denture (RPD) components. Compared to conventional methods, 3D-printed frameworks demonstrate superior fit and precision. The digital workflow involves data acquisition, virtual design, and digital wax-up of the framework, followed by fabrication using selective laser sintering or casting from a resin-printed pattern. Traditional techniques, which rely on manual steps like waxing and casting, are more time-consuming and less accurate. In contrast, digital scans allow for faster and more precise production using materials such as polymers or metals. A clinical trial comparing 3D-printed and conventionally fabricated dentures found that patients with 3D-printed RPDs experienced fewer tender points, enhanced chewing efficiency, and greater overall satisfaction.[19,20]

#### *3.8.4. Custom trays*

They are essential for impression-taking, bite registration, and temporary restoration fabrication. Traditionally made by hand from acrylic or silicone over stone casts, their production was time-consuming and technique-sensitive. However, with 3D printing and digital oral scanning, custom trays can now be produced more quickly and accurately, enhancing fit and clinical efficiency. Schmidt et al. compared four types of impression trays-conventional custom, customized foil, and two chairside 3D-printed trays (SHERA and Primeprint) using a model with four implants. Measurements with a coordinate measuring machine showed that chairside 3D-printed trays had the highest accuracy, followed by conventional custom trays, while customized foil trays were the least accurate. Significant differences were found between 3D-printed trays and the others ($p < 0.05$), with implant position not affecting accuracy. These results indicate that chairside 3D-printed trays significantly improve the precision of implant impressions.[21,22]

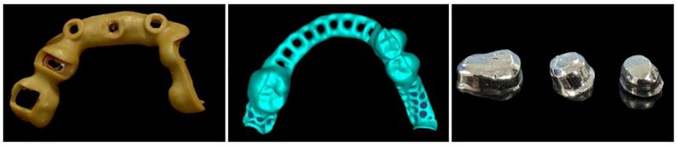

**Figure 3:** 3d Printing of tooth-supported surgical guide, Cast partial denture framework, and metal copings

#### *3.8.5. Application of 3D printing in fixed prosthodontics (**Figure 3**)*

3D printing has significantly improved fixed prosthodontics by enhancing accuracy and efficiency. Wax patterns for crowns and partial dentures are now created by digitally scanning the arches, designing in CAD software, and producing via 3D printing. Crown copings can also be directly printed from digital designs. Metal prostheses are fabricated using selective laser sintering or melting, eliminating the traditional wax pattern process and reducing errors. 3D printing also allows precise ceramic casting mold creation without wax patterns. For all-ceramic restorations, additive manufacturing like inkjet printing zirconia powder offers advantages over CAD/CAM milling by reducing material waste and enabling complex designs, with final sintering ensuring strength.[23,24]

A systematic review by Jain S evaluated the physical and mechanical properties of 3D-printed provisional crowns and FDP resin materials compared to CAD/CAM milled and conventional resins. The review concluded that 3D-printed provisional materials have better mechanical but poorer physical properties than CAD/CAM and conventional ones, making them a viable alternative for long-term provisional restorations.[25]

### *3.9. Application of 3d printing in dental implants*

3D printing in implantology offers significant advancements, including the fabrication of individualized titanium and zirconia implants using techniques like Electron Beam Melting (EBM) and Stereolithography (SLA). These implants demonstrate comparable osseointegration, survival rates, and mechanical properties to traditional ones, although standardized protocols are still lacking.

Accurate implant placement is crucial for successful outcomes, and additive manufacturing has greatly enhanced this precision. 3D-printed surgical guides enable accurate and safe implant positioning by precisely transferring the digital treatment plan to the surgical site. These guides are fabricated using biocompatible resins that comply with ISO 10993 standards, ensuring they are safe for intraoral use, suitable for sterilization, and translucent to enhance visibility during procedures. Proper sterilization of the surgical guide is essential, as inadequate sterilization can lead to infections at the osteotomy site.[26]

### *3.10. Application of 3d printing in maxillofacial prosthodontics*

Advancements in rapid prototyping have significantly contributed to the rehabilitation of maxillofacial defects, offering precise replication of complex anatomical structures. In maxillofacial prosthodontics, 3D printing is widely applied in the fabrication of customized prostheses and devices, including:[27,28]

1. Ocular, auricular, nasal, and other facial prostheses
2. Obturators for patients with partial or total maxillectomy
3. Radiation shielding devices to safeguard surrounding healthy tissues during radiotherapy
4. Burn stents, eliminating the need for painful traditional impressions
5. Surgical stents for guided excision of pathological tissues
6. Patient-specific anatomical models for mock surgeries and treatment planning
7. 3D visual models to enhance understanding of facial anatomy and defect areas

### *3.11. Future directions and opportunities*

Three-dimensional (3D) printing has brought a paradigm shift in dentistry, offering unprecedented accuracy, customization, and efficiency. Today, it plays a pivotal role across nearly all branches of dentistry, from prosthodontics to orthodontics and implantology. The next frontier appears to be its integration into tissue engineering, where researchers are leveraging 3D printing for developing biocompatible scaffolds that can support and stimulate the growth of tissues through the delivery of growth factors and biomolecules.

In prosthodontics, the future of 3D printing holds significant promise. To fully harness its potential, certain directions must be considered:

1. Rigorous Clinical Evaluation: Continued research is essential to evaluate the long-term quality, strength, and biological compatibility of 3D-printed prostheses. Standardized protocols are needed to assess various materials, print resolutions, and software platforms used in prosthodontics.
2. Economic Viability: While 3D printing can potentially reduce fabrication time and labor costs, its initial investment remains high. Comprehensive cost-benefit analyses should be conducted to determine its feasibility across different socioeconomic settings and healthcare systems.
3. Material Innovation: Future advancements should focus on the development of next-generation printable biomaterials that closely mimic natural tissues in both function and aesthetics, particularly for maxillofacial prostheses and long-term provisional restorations.
4. Education and Training: The successful implementation of 3D printing in dental practice demands that clinicians receive structured training. Incorporating 3D design and printing modules into dental curricula and continuing education will be crucial in building confidence and competence among dental professionals.
5. Interdisciplinary collaboration: Encouraging partnerships between engineers, material scientists, and dental specialists can foster innovations that push the boundaries of what 3D printing can achieve in clinical dentistry.

## 4. **Discussion**

A recent scoping review by Pradíes et al. explored the current applications of 3D printing in dental implantology by evaluating 132 relevant studies. The review highlighted three main areas: the use of additive manufacturing (AM) for customized dental implants, fabrication of surgical guides, and the production of implant-supported prosthetic components. While early evidence on the performance of AM titanium and zirconia implants is promising, clinical data remain limited. Surgical guides produced using 3D printing, particularly via MultiJet technology, show high accuracy when manufacturer protocols are followed. Additionally, advancements in 3D printed metallic frameworks and superstructures indicate significant improvements in quality, although milling still offers superior fit and strength in some cases. Valenti et al. conducted a systematic review and meta-analysis comparing the mechanical properties of 3D printed prosthetic materials with those fabricated using milling and conventional techniques. Based on 76 in vitro studies, the review found that while additive manufacturing (AM) is generally comparable to subtractive milling (MM) in aspects like marginal fit, roughness, and internal accuracy, its mechanical strength—especially flexural strength, hardness, and fracture load—is lower than MM and conventional processing. These limitations restrict AM prostheses mainly to interim restorations. However, its comparable performance in specific parameters indicates potential, especially in polymer-based applications.[29]

Zhang et al. demonstrated the successful additive manufacturing of zirconia dental implants with integrated directional surface pores using nano-particle inkjetting. These implants exhibited high mechanical strength, with fracture loads exceeding 500 N and further increasing after thermo-mechanical aging due to induced compressive stress at the dense core–porous surface interface. Importantly, the engineered porous surface facilitated favorable osteoblast responses, including enhanced cell orientation, attachment, proliferation, and matrix mineralization. This study highlights how additive manufacturing can overcome limitations of conventional methods by simultaneously delivering biomechanical durability and improved biological integration in ceramic implants.[30]

Kouhi et al. (2024) comprehensively reviewed recent advances in additive manufacturing (AM) for fabricating patient-specific devices in dental and maxillofacial rehabilitation. The paper highlights how 3D printing technologies are being increasingly adopted across various specialties, including prosthodontics, implantology, maxillofacial surgery, orthodontics, periodontics, and endodontics, for producing custom devices tailored to individual anatomical needs. The review also discusses material considerations, clinical outcomes, and emerging innovations such as 4D printing. Overall, the study underscores the transformative role of AM in enhancing precision, personalization, and clinical outcomes in modern dental care.[31]

## 5. Conclusion

3D printing has emerged as a transformative technology in prosthodontics, offering unparalleled precision, customization and efficiency in the fabrication of dental restorations and maxillofacial prostheses. Its integration into removable and fixed prosthodontics, implantology, and maxillofacial rehabilitation has improved clinical outcomes by enhancing fit, reducing production time, and enabling patient-specific solutions that were previously challenging with conventional methods. Future advancements focusing on material innovation, standardized clinical evaluation, economic feasibility, and expanded educational efforts are essential to fully realize the potential of 3D printing in prosthodontics. Moreover, interdisciplinary collaboration among clinicians, engineers, and material scientists will drive further innovation, ultimately improving patient care and advancing the field toward a more digital and personalized era of dentistry.

## 6. Source of Funding

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## 7. Conflict of Interest

None.

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