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Three-dimensional Printing in Dentistry: From Digital Workflow to Clinical Applications

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ABSTRACT

Three-dimensional (3D) printing has become an important technology in modern digital dentistry, enabling the fabrication of customized dental structures directly from digital designs. This narrative review highlights the basic digital workflow of 3D printing, including scanning, computer-aided design, printing, and post-processing. Its applications in prosthodontics, implant dentistry, orthodontics, restorative dentistry, and oral surgery are discussed. The major advantages, including customization, accuracy, reduced material wastage, and efficient fabrication, are considered along with limitations such as cost, material properties, post-processing requirements, and technical expertise. With continued advances in materials, artificial intelligence, and digital workflows, 3D printing is expected to play an increasingly important role in clinical dentistry.

INTRODUCTION

Three-dimensional printing, also known as additive manufacturing, has emerged as a transformative technology in modern dentistry.[1] Unlike conventional manufacturing techniques that involve cutting or shaping materials, 3D printing creates objects layer by layer from a digitally designed model.[2] The integration of digital imaging, intraoral scanning, computer-aided design (CAD), and computer-aided manufacturing (CAM) has made this technology increasingly accessible in clinical and laboratory practice.[3]

The applications of 3D printing have expanded considerably across various dental specialties. In prosthodontics, it is used for diagnostic models, custom trays, provisional restorations, denture bases, occlusal splints, and prosthetic components. In implant dentistry, 3D printing facilitates the fabrication of surgical guides and patient-specific prosthetic components. Orthodontics and oral and maxillofacial surgery have also benefited through the production of aligners, study models, surgical guides, and anatomical replicas.[4,5]

A typical 3D-printing workflow involves digital data acquisition, computer-aided design, file preparation and slicing, printing, and post-processing. The choice of printing technology and material depends on the intended application, required accuracy, mechanical properties, and clinical requirements. Common technologies include stereolithography (SLA), digital light processing (DLP), and material extrusion.[6]

Despite its advantages, including customization, reproducibility, efficient material utilization, and streamlined digital workflows, 3D printing has certain limitations. Printing accuracy may be influenced by factors such as layer thickness, printing orientation, material characteristics, and post-processing procedures. Cost, technical expertise, equipment maintenance, and the long-term performance of printed materials also remain important considerations.

This narrative review discusses the evolution of 3D printing in dentistry, its digital workflow, major technologies and materials, current clinical applications, advantages and limitations, and emerging developments that may shape the future of digital dental practice.

Principle of 3D Printing

Three-dimensional (3D) printing is an additive manufacturing process in which a physical object is produced by depositing or selectively solidifying material layer by layer according to a digitally designed three-dimensional model. The process begins with the acquisition of digital data through intraoral scanning, laboratory scanning, or medical imaging. The digital model is then designed or modified using computer-aided design (CAD) software and converted into a printable file, commonly an STL (Standard Tessellation Language) file.

The STL file is imported into slicing software, which divides the model into a series of thin horizontal layers and generates the instructions required by the printer. During printing, the selected material is deposited, cured, or selectively solidified layer by layer until the complete object is formed. The printed structure is subsequently subjected to post-processing, which may include washing, removal of support structures, curing, polishing, and finishing.

Thus, the basic principle can be summarized as: Digital data acquisition ⟶ CAD design ⟶ STL conversion ⟶ Slicing ⟶ Layer-by-layer fabrication ⟶ Post-processing ⟶ Final dental product

In dentistry, this principle allows the fabrication of patient-specific models, surgical guides, denture bases, provisional restorations, occlusal splints, orthodontic appliances, and other prosthodontic components with a largely digital workflow.[7,8]

Three-Dimensional Printing Systems

Various 3D-printing technologies have been developed for dental applications, each based on a different method of material deposition or polymerization. The most commonly used systems include stereolithography (SLA), digital light processing (DLP), liquid crystal display (LCD) printing, and fused deposition modeling (FDM). These technologies differ in terms of printing mechanism, accuracy, resolution, production speed, material requirements, and clinical applications. A summary of the major 3D-printing systems used in dentistry is presented in Table 1.[9]

Three-Dimensional Printing in Prosthodontics

Three-dimensional (3D) printing has become an important component of digital prosthodontics, enabling the fabrication of customized prosthetic restorations and appliances directly from digital designs. The workflow typically involves intraoral or laboratory scanning, digital designing, slicing, printing, and post-processing, providing an integrated digital approach to prosthetic rehabilitation.

In removable prosthodontics, 3D printing is increasingly used for diagnostic casts, custom impression trays, denture bases, artificial teeth, complete dentures, and occlusal splints. Digital fabrication allows patient-specific designs, easy duplication of prostheses, and efficient storage of digital records. Compared with conventional processing, it may reduce laboratory steps and fabrication time while improving workflow reproducibility.

In fixed prosthodontics, additive manufacturing can be used for provisional restorations, patterns, models, and selected prosthetic components. It also facilitates the production of complex geometries with relatively efficient material utilization. In implant prosthodontics, 3D printing is useful for implant surgical guides, diagnostic models, provisional prostheses, and customized components, particularly when integrated with CBCT and digital scanning.

Despite these advantages, limitations include material degradation, polymerization shrinkage, dimensional changes, surface roughness, post-processing requirements, and variations in mechanical properties. The long-term clinical performance of some printed materials also requires further investigation. Overall, 3D printing is progressively transforming prosthodontic practice by promoting personalized treatment, digital reproducibility, efficient fabrication, and integration of clinical and laboratory workflows.[10-12]

Three-Dimensional Printing in Implantology

Three-dimensional (3D) printing has significantly improved digital workflows in implant dentistry by enabling patient-specific treatment planning and fabrication of customized surgical guides. The integration of cone-beam computed tomography (CBCT), intraoral

Table 1

Table 1. Major Three-Dimensional Printing Systems Used in Dentistry				
3D Printing System	**Principle**	**Advantages**	**Limitations**	**Dental Applications**
Stereolithography (SLA)	UV laser selectively polymerizes liquid photosensitive resin layer by layer	High accuracy; excellent resolution; fine detail reproduction	Requires washing and post-curing; support structures may be required	Diagnostic models, surgical guides, denture bases, provisional restorations, occlusal splints
Digital Light Processing (DLP)	Projected light polymerizes an entire resin layer simultaneously	Faster printing; good accuracy; suitable for batch production	Material and printer dependent; post-processing required	Denture bases, surgical guides, provisional restorations, occlusal appliances
LCD Printing	UV light passes through an LCD screen to selectively polymerize resin	Good resolution; relatively low equipment cost; rapid fabrication	LCD components have limited lifespan; accuracy depends on exposure and resin parameters	Models, surgical guides, denture bases, provisional restorations, appliances
Fused Deposition Modeling (FDM)	Heated thermoplastic filament is extruded layer by layer	Low cost; simple operation; minimal material wastage	Lower resolution; visible layer lines; finishing may be required	Diagnostic models, prototypes, custom trays, educational models

scanning, and CAD software allows accurate virtual implant positioning before surgery.

One of the major applications is the fabrication of static implant surgical guides, which assist in controlling implant position, angulation, and depth. This is particularly useful in anatomically challenging cases and can improve surgical precision while reducing unnecessary bone removal and operative time. 3D-printed models can also be used for preoperative planning, anatomical assessment, and patient education.

In implant prosthodontics, additive manufacturing is increasingly used for provisional restorations, diagnostic models, custom impression trays, and prosthetic components. The technology facilitates rapid fabrication and easy reproduction of patient-specific designs. It can also support immediate-loading workflows by allowing provisional prostheses to be designed and fabricated before implant placement.

However, the accuracy of 3D-printed implant guides can be affected by CBCT and scanning errors, image registration, printer accuracy, guide stability, printing orientation, and post-processing. Therefore, careful digital planning and clinical verification remain essential.

Overall, 3D printing has become an important component of modern implantology, particularly for guided implant surgery, digital treatment planning, and customized prosthetic rehabilitation, although further clinical evidence is needed to establish standardized protocols and long-term outcomes.[13]

Three-Dimensional Printing in Orthodontics

Three-dimensional (3D) printing has significantly expanded the scope of digital orthodontics by enabling the fabrication of accurate dental models and customized appliances. Its applications include diagnostic models, indirect bonding trays, clear aligners, aligner molds, retainers, and mouth guards. The workflow generally involves digital scanning, virtual treatment planning, CAD-based design, and additive manufacturing using technologies such as SLA and DLP.

3D printing allows orthodontic appliances to be digitally designed according to individual patient anatomy, improving customization and reproducibility. It can also reduce laboratory procedures, fabrication time, and material wastage compared with conventional techniques. Digital models facilitate virtual treatment simulation and storage of patient records, while 3D-printed indirect bonding trays can improve bracket positioning and procedural efficiency. Clear aligners produced through digitally planned workflows provide an esthetic alternative to conventional fixed appliances and can offer improved patient comfort.

Three-dimensionally printed occlusal splints have also gained attention in the management of temporomandibular disorders, where digital design may improve appliance adaptation and simplify fabrication. However, the clinical performance of printed orthodontic appliances can be influenced by printing parameters, resin composition, post-processing, wear, and dimensional stability. Some materials may undergo changes in physical properties or develop fractures during prolonged clinical use. Therefore, appropriate material selection, standardized printing protocols, and adequate post-processing are essential for predictable clinical outcomes.

Overall, 3D printing represents a valuable component of contemporary orthodontic practice, supporting personalized treatment planning, efficient appliance fabrication, digital record keeping, and improved integration of clinical and laboratory workflows.[14,15]

Three-Dimensional Printing in Endodontics

Three-dimensional (3D) printing has increasingly contributed to endodontic diagnosis, treatment planning, surgical procedures, education, and research. Its most important clinical application is the fabrication of patient-specific endodontic surgical guides, particularly for complex cases involving calcified canals, unusual root anatomy, and periapical surgery.

The integration of cone-beam computed tomography (CBCT) with intraoral or surface scanning allows the creation of virtual treatment plans and customized surgical guides. Technologies such as stereolithography (SLA) and PolyJet can produce highly accurate guides that help control the location, angulation, and depth of access or osteotomy. Guided endodontic procedures may improve the localization of calcified canals, reduce unnecessary removal of tooth structure, and decrease procedural errors and treatment time.

3D-printed models are also valuable in preclinical education and training, allowing students and clinicians to practice procedures on anatomically realistic replicas. Despite these advantages, current evidence is largely based on laboratory studies and case reports, with limited long-term clinical data. Factors such as printing accuracy, guide adaptation, material properties, and workflow-related errors may influence clinical outcomes. Further clinical research is therefore required to establish standardized protocols and determine the long-term effectiveness of 3D-printed applications in endodontics.[16]

Three-Dimensional Printing in Oral Surgery

Three-dimensional (3D) printing has emerged as a valuable technology in oral surgery, particularly for preoperative planning, surgical simulation, fabrication of patient-specific guides, and reconstruction. The integration of CBCT imaging with digital surface scans allows clinicians to create accurate three-dimensional anatomical models and develop individualized surgical plans.

A major application is the fabrication of 3D-printed surgical guides, which can assist in procedures such as implant placement, apical surgery, bone harvesting, and complex tooth removal. Patient-specific anatomical models can also help clinicians visualize complex structures, anticipate surgical difficulties, and improve communication with patients.

In maxillofacial surgery, 3D printing facilitates the fabrication of anatomical models, cutting and drilling guides, reconstruction plates, and customized prosthetic components. It can improve surgical accuracy, reduce operative time, and support more predictable reconstruction. In addition, 3D-printed models are useful for undergraduate and postgraduate surgical training, allowing repeated practice without using patients.

Despite these advantages, limitations include printing time, material costs, technical expertise, dimensional inaccuracies, and dependence on the quality of imaging and digital data. The clinical usefulness of printed guides also depends on their stability and accurate intraoperative positioning.

Overall, 3D printing is transforming oral surgery by providing patient-specific surgical planning, improved procedural precision, enhanced education, and customized reconstructive solutions.[17]

Other Applications of 3D Printing in Dentistry

Beyond prosthodontics, implantology, orthodontics, and oral surgery, 3D printing has diverse applications across dentistry. In restorative dentistry, it can be used for provisional restorations, customized matrices, models, and experimental restorative components. In pediatric dentistry, 3D printing facilitates the fabrication of customized trays, diagnostic models, and treatment-planning aids. In periodontology, it has potential applications in the production of surgical guides, anatomical models, and regenerative scaffolds. In maxillofacial prosthetics, 3D printing enables the fabrication of patient-specific facial, orbital, and auricular prostheses. It is also increasingly used in dental education and training through realistic anatomical and pathological models that allow simulation of clinical procedures. Additionally, 3D printing has applications in forensic dentistry, patient education, research, tissue engineering, and regenerative dentistry. Emerging technologies such as bioprinting, smart biomaterials, artificial intelligence-assisted design, and 4D printing may further expand its role in personalized and regenerative dental care.[3-5]

Future Perspectives of 3D Printing in Prosthodontics

The future of 3D printing in prosthodontics is expected to focus on faster, more accurate, and increasingly per-

Table 2

Table 2: Advantages and Limitations of 3D Printing in Dentistry	
Advantages	**Limitations**
High degree of customization and patient-specific fabrication	High initial cost of printers and software
Rapid fabrication of dental models and appliances	Requires technical knowledge and digital skills
High accuracy and reproducibility	Accuracy may be affected by printing parameters and orientation
Reduced material wastage compared with subtractive methods	Some materials have limited long-term durability
Complex anatomical structures can be fabricated	Post-processing such as washing, curing, and polishing is often required
Easy digital storage and reproduction of dental designs	Printing errors may occur due to software, scanning, or hardware issues
Facilitates integration with CAD/CAM and digital scanning	Material selection is limited for certain clinical applications
Reduces some laboratory procedures and workflow time	Surface roughness may require additional finishing
Useful for treatment planning and surgical simulation	Equipment maintenance and calibration are required
Supports personalized and minimally invasive treatment	Limited long-term clinical evidence for some newer materials
Useful for education, training, and patient communication	Regulatory and biocompatibility concerns may apply to some printed materials

sonalized prosthetic rehabilitation. Advances in printable biomaterials may improve the strength, esthetics, durability, and biocompatibility of denture bases, crowns, bridges, and implant-supported prostheses. Integration of artificial intelligence (AI), intraoral scanning, CAD/CAM, and digital facial scanning may enable automated prosthesis design and more precise patient-specific treatment planning. The development of multi-material and bioprinting technologies may allow fabrication of prostheses with improved functional and biological characteristics. In addition, 4D printing and smart materials may provide prosthetic components capable of responding to changes in the oral environment. As printing technologies become more affordable and standardized, chairside and same-day fabrication of prostheses may become increasingly feasible. Overall, 3D printing is likely to further shift prosthodontics toward a fully digital, customized, efficient, and patient-centered workflow.

CONCLUSION

Three-dimensional printing has emerged as a transformative technology in modern dentistry, integrating digital imaging, CAD/CAM, and additive manufacturing into clinical practice. Its applications extend across prosthodontics, implantology, orthodontics, endodontics, oral surgery, and dental education. The ability to fabricate customized, accurate, and reproducible dental structures offers significant advantages in treatment planning and clinical efficiency. However, limitations related to material properties, printing accuracy, post-processing, cost, and long-term clinical evidence remain. Continued advances in printable materials, artificial intelligence, and digital workflows are expected to further expand the role of 3D printing and support more predictable, personalized, and efficient dental care.

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