3D Printing in Dentistry: From current applications to future potential

Abstract

Advancements in 3D printing have transformed dentistry by enabling the precise fabrication of patient-specific prosthetics, scaffolds, and implants. However, conventional 3D printing materials are limited by their static properties, restricting their adaptability to dynamic oral environments. The emergence of 4D printing, incorporating time as an additional dimension, allows the use of smart materials capable of responding to specific stimuli. This technology shows promise in tissue reconstruction, endodontics, dental implants, and prosthetic devices by improving adaptability, reducing fracture risk, and enhancing tissue integration. Innovations such as shape-memory elastomers, hydroxyapatite-reinforced polymers, and surface-modified metals enhance mechanical strength, bioactivity, and antibacterial properties. Despite the potential of metal 3D printing, its high cost and technical complexity limit its widespread application. Ongoing research focuses on optimizing biomaterial selection, printing techniques, and digital workflows to maximize clinical outcomes in regenerative and restorative dentistry.

Background

Three-dimensional (3D) printing, also known as additive manufacturing (AM), has become an integral component of digital dentistry, fundamentally altering the way dental devices are designed and fabricated. Unlike subtractive manufacturing techniques, additive manufacturing builds objects layer by layer from digital datasets, allowing the production of complex geometries with high precision and reduced material waste. Over the past decade, advances in computer-aided design/computer-aided manufacturing (CAD/CAM), imaging technologies, and printable biomaterials have accelerated the adoption of 3D printing across multiple dental specialties.[1,2]

In contemporary clinical practice, 3D printing is widely applied in prosthodontics for the fabrication of crowns, bridges, complete and partial dentures, provisional restorations, and implant-supported frameworks. These applications have demonstrated improved accuracy, reproducibility, and efficiency compared with conventional laboratory workflows, while also enabling greater customization to individual patient anatomy.[3,4] Orthodontics has similarly benefited from additive manufacturing through the production of diagnostic models, clear aligners, retainers, and indirect bonding trays, enhancing treatment planning and predictability.[2,5]

In oral and maxillofacial surgery and implant dentistry, 3D printed surgical guides and anatomical models derived from cone-beam computed tomography (CBCT) data have improved preoperative planning, implant positioning accuracy, and intraoperative efficiency.[1,4] These patient-specific guides contribute to reduced surgical time and increased procedural safety. Beyond direct patient care, 3D printing has also gained prominence in dental education and training, where printed models provide cost-effective, reproducible, and anatomically accurate tools for preclinical simulation and skill development.[7]

Several additive manufacturing technologies are currently employed in dentistry, including stereolithography (SLA), digital light processing (DLP), fused deposition modeling (FDM), selective laser sintering (SLS), and material jetting. Each technique differs in terms of resolution, printing speed, mechanical properties, and material compatibility, influencing its suitability for specific dental applications.[3,6] Printable materials used in dentistry include photopolymer resins, thermoplastics, metals, and emerging ceramic-based systems, many of which have been developed to meet regulatory and biocompatibility requirements for intraoral use.[3,5]

Despite its rapid growth, the clinical implementation of 3D printing in dentistry is not without limitations. Challenges remain related to long-term material stability, mechanical strength, post-processing requirements, accuracy across different printers, and standardization of clinical protocols.[2,6] Looking ahead, ongoing research into artificial intelligence–assisted design, hybrid manufacturing workflows, and bioprinting is expected to expand the scope of additive manufacturing toward regenerative and tissue-engineering applications. Continued evidence-based evaluation is essential to define best practices and ensure safe, predictable clinical outcomes.[1,3]

Materials Used in Dental 3D Printing:

The paradigm shift from analog, subtractive manufacturing to digital or 3D represents one of the most significant technological disruptions in the history of dentistry. While Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) initially gained prominence through subtractive milling, 3D printing has expanded the geometric and functional possibilities of dental biomaterials. By constructing objects layer-by-layer, it circumvents the geometric limitations of milling tools, reduces material waste and enables the fabrication of complex internal structures.[8]

The efficacy and safety of 3D-printed dental devices are undoubtedly linked to the underlying materials science. As the field advances toward 2026, the industry is witnessing a transition from inert prototyping materials to bioactive, high-performance smart materials.[9]

<u>Polymer-Based Materials in Dental 3D Printing</u>

Polymers are the most ubiquitous class of materials in dental 3D printing, utilizing vat photopolymerization (SLA/DLP) and extrusion (FDM) to achieve a wide range of mechanical properties.[8]

1. Photopolymer Resins

Liquid monomers polymerized by UV light (385 nm or 405 nm) formulated with photoinitiators and specific additives.

a Diagnostic and Model Resins

Methacrylate formulations for high reactivity and low shrinkage. A matte finish and specific opacity are critical to prevent overcure and ensure readability by desktop scanners. High-temp variants are required for aligner manufacturing to withstand the heat/pressure of vacuum thermoforming without deformation.[8]

Used in diagnostic models and orthodontic aligner molds.

b Surgical Guide Resins

Class I biocompatible. High flexural modulus is essential to prevent bending during drilling, while optical transparency allows visualization of guide seating. Must maintain dimensional stability after autoclaving.[10]

Used in Implant surgical guides.

c Restorative Resins

Provisional (Temporary): Typically unfilled methacrylates designed for short-term aesthetics and polishability (Flexural strength >50 MPa).[8]

Permanent**:** Ceramic-Polymer Nanohybrids with high ceramic loading (30–50%). These Class IIa materials offer high flexural strength (>120–150 MPa) and wear resistance comparable to composites.[8]

Used in temporary and permanent crowns, bridges and inlays.

d Denture Base and Teeth Resins

Bases require high impact strength; teeth require wear resistance and translucency. Multi-material jetting now allows for monolithic printing of both base and teeth with seamless interfaces.[12]

Used in full and partial digital dentures.

2. High-Performance Thermoplastics (PAEK Family)

Semi-crystalline thermoplastics processed via FDM or SLS, offering mechanical properties that challenge metallic alloys.

a PEEK (Polyetheretherketone)

Elastic modulus (3–4 GPa) closely matches human cortical bone, reducing stress shielding compared to titanium. High melting point (~343°C) and rapid crystallization require heated chambers to prevent warping.[13]

Used in RPD frameworks, healing abutments and provisional bridges.

b PEKK (Polyetherketoneketone)

Slower crystallization rate than PEEK allows for a wider processing window and superior layer adhesion. Exhibits ~80% higher compressive strength and superior shock absorbance, protecting prosthetic screws from stress.[13]

Used in Implant-supported frameworks and high-stress bars.

3. Metallic Materials

Metals are processed primarily via Selective Laser Melting (SLM) to create dense, load-bearing structures.

a Titanium Alloys (Ti-6Al-4V)

Exceptional biocompatibility. SLM printing enables the fabrication of porous, trabecular-like outer lattices for enhanced osseointegration (secondary stability) while maintaining a dense core.[12]

Used in Dental implants and reconstruction meshes.

b Cobalt-Chromium (CoCr)

High stiffness (Modulus ~220 GPa) and corrosion resistance. 3D-printed CoCr exhibits higher Vickers hardness (371 ± 10 HV) than cast alloys allowing for thinner, more delicate clasp designs without fracture risk.[12]

Used in RPD frameworks and PFM copings.

c Metal Powder

Strict requirements for sphericity (>98%) and particle size (15–45 µm) to ensure flowability and uniform density. Irregular particles cause porosity defects.[12]

4. Ceramics and Glass-Ceramics

Ceramics offer superior aesthetics and biocompatibility but present processing challenges due to brittleness. 3D printing ceramics presents difficulties primarily due to their high melting points, which often lead to the formation of cracks during the cooling phase. Furthermore, the selection of raw materials significantly influences both the resulting porosity and the ultimate mechanical properties of the ceramic product.[10]

a Zirconia (ZrO2)

Printed via SLA using ceramic slurry. Zirconia (Bioceramic) is employed extensively within dentistry as they exhibit characteristics comparable to natural dentition including compressive strength, thermal conductivity, radiopacity, color stability, and aesthetic properties. Nevertheless, these materials are characterized by inherent brittleness, hardness and may present challenges in processing.[14] 3D-printed Zirconia using SLA technique achieves flexural strengths of 942-1519 MPa, whereas conventional methods yield flexural strength of 900-1200 MPa.[15]

Used in posterior crowns, bridges, inlays/onlays and implant abutments.

b Lithium Disilicate

Using DLP 3D printing technique for this material results in increased density, flexural strength >400 MPa but significantly higher translucency and accuracy. Structures created through 3D printing can achieve properties comparable to those produced by traditional milling methods.[15]

Used in anterior veneers and single crowns.

5. Novel and Advanced Materials

a) Graphene-Reinforced Composites

Incorporation of Graphene Oxide (GO) or Nanoplatelets (GNPs) into polymers (like PMMA). Low concentrations (~0.027 wt%) significantly enhance flexural strength and hardness by inhibiting crack propagation.[16] Also exhibits antimicrobial properties against *Candida albicans*.[17]

Used in reinforced dentures and long-term splints.

b) 4D Printing and Smart Materials

Utilizes Shape Memory Polymers (SMPs) that transform shape upon exposure to stimuli (heat/moisture) post-printing. This adds the dimension of time to the fabrication process.[9]

6.Synthetic Polymers

Synthetic polymers such as Polycaprolactone (PCL), Polylactic Acid (PLA), Pluronic and Polyethylene Glycol (PEG) are extensively utilized in biological 3D printing and show promise for 4D printing applications. These polymers offer advantages like low cost, mass production, chemical stability and appropriate degradation rates. PEG specifically improves the mechanical properties of bioinks. Pluronic, a block copolymer, forms self-assembled gels at room temperature. However, the key drawback is their lower biocompatibility compared to natural polymers.[18]

7.Natural Biopolymers

Natural biopolymers are biocompatible and biodegradable, mimicking the extracellular matrix (ECM) structure and properties. Common examples for 4D printing bioinks include hyaluronic acid (HA), collagen, agarose, chitosan, and alginate. HA-based hydrogel bioinks offer high mechanical properties and stability and hydrogels simulate the ECM microenvironment supporting cell functions. Collagen can be used alone or in combination (alginate, gelatin) to improve mechanical properties. Agarose often requires additives (collagen, fibrinogen, alginate) to enhance cell growth and mechanical properties. Chitosan has good biocompatibility but low mechanical strength, which can be improved with calcium ion addition. Cellulose is used in scaffolds and drug delivery with cellulose materials like nanocrystals added to hydrogels to increase viscosity and printing accuracy.[18]

8.Cells

Cells are crucial for bioinks used in tissue and organ regeneration. For 4D printing applications, suitable cell types often include Mesenchymal Stem Cells (MSCs) and osteoblasts. Bioinks can be formulated by combining cells with scaffold biomaterials or solely by cell aggregates or spheroids. Various dental cells (Dental Pulp Stem Cells, Periodontal Ligament Stem Cells) and non-dental cells (bone marrow stem cells, pre-osteoblasts) are currently employed in 4D printing for the regeneration of maxillofacial structures and teeth.[18]

9.Growth Factors

Growth factors are signalling molecules that control cell growth and differentiation by binding to the ECM. Their selective release is vital for bioactivity. They are incorporated into materials like natural/synthetic polymers within sponges, micro/nanoparticles and hydrogels to promote tissue regeneration such as bone (e.g., Stromal cell Derived Growth Factor-1, Bone Morphogenic Protein).[18]

The landscape of dental additive manufacturing materials has evolved from a niche prototyping capability into a comprehensive clinical ecosystem. As of now the domain is defined by the synergy between material chemistry and machine physics. We are witnessing the displacement of traditional materials: PEKK is challenging Titanium in implant frameworks due to its superior shock-absorbing biomechanics, Nanohybrid Resins are bridging the gap between the elasticity of composites and the aesthetics of ceramics and 4D Smart Materials are poised to transform passive appliances into active therapeutic devices.[8,9,13]

Current Applications of 3D Printing in Dentistry:

<u>Applications In Orthodontics:</u>

Clear Aligners:

Clear aligner therapy has been revolutionized by 3D printing technology, which enables creation of complex geometric structures with high precision and has transformed orthodontic treatment worldwide.[19,20]There are two main approaches:

Traditional Thermoforming Method:

- Most current clear aligners are produced through thermoforming using thermoplastic materials, though this process alters material properties and affects overall performance.[21]

Direct 3D Printing (Emerging):

- Direct 3D printing offers creation of highly precise clear aligners with soft edges that are digitally designed and identically reproduced for entire treatment sets, offering better fit, higher efficacy, and reproducibility.[21]
- Scientific evidence is primarily available for Tera Harz TC material, which is the only studied material approved for orthodontic tooth movements.[22]

- Direct-printed aligners distinguish themselves with shape memory and design flexibility properties, exerting more consistent force profiles than thermoformed aligners with higher accuracy, trueness and precision.[23]

Orthodontic Models and Appliances

- 3D-printed models are utilized for diagnosis and treatment planning, with orthodontists using this technology to produce many different appliances with faster turnaround times.[24,25]
- Models can be printed rapidly - for example, 11 models in nine minutes achieving ROI in four to five cases

Market Growth

The orthodontics segment dominated the dental 3D printing market in 2024 with 40% market share, with the market projected to grow at a CAGR of 26.42% from 2025 to 2034.[26]

<u>Applications in Prosthodontics:</u>

Crowns and Bridges

3D printing creates detailed restorations including crowns, bridges, and implant-supported frameworks using technologies like stereolithography and digital light processing.[27]

Material Properties:

- 3D-printed resins contain from 3% to 50% filler content with various methacrylate resins, though they currently have lower flexural strength, modulus, and hardness than conventional and milled materials.[28]
- Advanced 3D-printed provisional restorations exhibit flexural strength ranging from 60 to 90 MPa and fracture resistance of 1000-1200 N, consistently matching or surpassing traditional manufacturing technique.[29]

Production Efficiency:

- Single-unit restorations are printable in approximately 20 minutes, allowing clinicians to prepare a tooth, scan it, initiate printing, and proceed with other treatments while the restoration is manufactured.[29]

Dentures

3D printing has transformed the creation of dentures and removable partial dentures, allowing for precise modeling and manufacturing that fits comfortably and securely.[27]

Surgical Guides

Specialized software is used to plan and fabricate guides that help surgeons accurately place dental implants, with examples including Simplant, NobelGuide, and X-Guide.[27]

3D PRINTING TECHNOLOGIES USED

Main Technologies:

1. **Stereolithography (SLA)** - Widely used for creating custom dental prostheses such as crowns and bridges, progressively replacing conventional fabrication methods due to its capacity to produce complex structures with intricate geometries.[27]
2. **Digital Light Processing (DLP)** - A rapid printing method that uses a light source to cure layers at once, widely used for dental restorations and orthodontic models, though it enhances mechanical properties it is restricted to photopolymers that emit odors.[27]
3. **Laser Sintering/Melting** - Successfully used since 2002 for metal alloys, now a standard process for production of CoCr crowns and bridges with stress-free and accurately fitting frameworks.[30]

ADVANTAGES

3D printing offers numerous clinical advantages including increased patient satisfaction and reduced production time.[31]

Key Benefits:

- High customization and precision
- Reduced production time
- Cost-effectiveness
- Material conservation
- Better fit and patient comfort
- Ability to create complex geometries
- Same-day/chairside delivery capability

<u>Applications In Maxillofacial surgery and Implant dentistry:</u>

The world is changing at a fast pace with changing realities resulting in a diverse population due to migration. This demands an individualized approach to each and every patient with unique anatomical features. The medical profession is adapting to the patient’s needs by providing a customized approach. The Oral and Maxillofacial surgeons and implantologists have welcomed the additive technology or 3D printing, which has made them achieve surgical precision by managing time effectively resulting in reduction of post-operative complications.

Researchers continue to incorporate new technologies in an attempt to achieve the best possible results. 3D printing which comes under additive manufacturing technologies, stands as a good example with bone substitute biomaterials like titanium, ceramics and polyetheretherketone (PEEK), which are commonly used in Oral and Maxillofacial Surgery.[38] Titanium alloy is known for its high modulus of elasticity and high strength when compared to bone, which leads to reduced stress on the bone leading to osteopenia. Ceramics weaken when there is a rise in PH. PEEK on the other hand is chemically stable and is inert in changing PH levels. These biomaterials lack osteoinductive properties. 3D printing plays a vital role in overcoming these shortcomings by engineered approach and precise composition. The 3D printed honey-comb pattern not only improves the stress bearing capability but also makes it much lighter. This enhances the osteointegration of the implant without compromising its mechanical properties. Nanohydroxyapatite biocomposites have proved to be compatible with 3D printing having bone mimicking properties. The fillers used in these biocomposites determine the flowability during 3D printing and the structural stability of these biocomposites after polymerization.[33]

Some of the commonly used 3D printing technologies in OMFS include;

1. Steriolethography (SLE),
2. Powder Bed Fusion / Selective Laser Sintering (SLS),
3. Material extrusion / Fused Deposition Modeling (FDM),
4. Direct Metal Laser Sintering (DMLS),

   Other technologies include Direct Energy Deposition, Binder Jetting, Material Jetting, Vat Polymerization (Stereolithography Apparatus -SLA, or Direct Light Processing-DLP), and Sheet Lamination (Laminated Object Manufacturing -LOM).[38,39]

In Oral and Maxillofacial Surgery, 3D printing has been used for:

1. Study models as patient education tools:

A virtual 3D model is required for 3D printing and this is made possible with the use of Computer-Aided Design (CAD) and Virtual Surgical Planning (VSP) tool box. 3D printed study models help in educating the patients so as to obtain realistic rather than a conceptualized informed consent.[38]

2. Customized cutting and positioning guides:

Surgical planning by utilizing CAD and 3D printed models to accurately perform osteotomies by fabricating positioning guides to replace the defects with 3D printed bone substituted biomaterials before the actual procedure, enhancing preoperative preparedness .[37,38]

3. Orthognathic surgery:

Virtual surgical planning and 3D printing have replaced the traditional 2D radiography (cephalometric analysis) and the dental stone models. Fabrication of ideal splints could be attained with careful application of these technologies.[38]

4. Tissue Engineering:

Regenerative scaffolds have played a vital role in Tissue Engineering. These regenerative scaffolds provide structural support to those deficient tissues and help in their regeneration. These scaffolds are made of scaffold matrix, stem cells and bioactive factors.[37]

5. Maxillofacial Implants:

Universal implants would undergo manipulation to fit those maxillofacial defects consuming a lot of operating time and yet would not be esthetically pleasing. The complex anatomy of these maxillofacial structures are hard to replicate with the conventional practices. The possibility of 3D printing these implants pre-operatively with precision, enhances the esthetics and replicates the complex anatomy resulting in successful outcomes.[37,38,39]

6. Management of TMJ diseases:

End stage TMJ diseases like osteoarthritis, ankylosis, tumors, and comminuted fractures require complete reconstruction of the joint. The commercially available prostheses match the anatomy of many but not all of the population. 3D printing has been used in all the three components of the joint, the fossa, head and the mandibular component. Different biomaterials are used in printing these components. Complex design and high costs are the major disadvantages. The data available on total replacement of the joint with 3D printing technology is very limited and needs more research.[37,38]

7. Dental Implants

3D printing is mainly used in these three circumstances in Implant dentistry

A. Fabrication of surgical implant guides
B. Custom made dental implants
C. Implant supported prostheses

A. Fabrication of surgical implant guides:

In Implant dentistry, guided implant surgeries use light curing polymers to fabricate surgical guides. Both the subtractive technologies like the CAD/CAM and the additive technology like the 3D printing have shown to be accurate in milling and printing the surgical implant guides especially when new industrial 3D printers were used rather than the moderately accurate in-office desktop printers.[37]

B. Custom made dental Implants:

Customized dental implants are usually porous and also fracture resistant. These properties help in better osteointegration and have bone-like properties. 3D printed customized dental implants when used as single implants have shown 94.5% survival rate at 3 years. Studies are carried out to replace both anterior and posterior teeth with implants simulating the anatomical roots which have shown good primary stability. Further studies are required to standardize these customized implants.[34]

CAD or CBCT and intra-oral scanners create digital models which guide the 3D printing technologies to print zirconia, titanium and polymer-based implants. Implants created by 3D printing mimic the trabecular pattern of the bone improving their biointegration. Although 3D printing has shown promising results with regards to accuracy, time and healing, less data and increased cost of the technology pose questions about their feasibility. 3D printed with hydroxy appetite zirconia implants integrate faster and show higher biomechanical properties even though zirconia is not used in those high stress bearing areas due to its brittleness.

Bioengineered, 3D printed biohybrid implants mimic the proprioceptive function of the periodontal ligaments giving patients the natural feel that may soon be possible. Robotic surgeries incorporating 3D printing and CBCT have been initiated with future clinical trials.[35]

C. Implant supported prostheses:

3D printed implant supported prostheses have their own limitations even though it does show promising results with the industrial 3D printers, subtractive technology at present is the most widely used and accepted technology since they deliver better mechanical properties and marginal fit.[34]

The 3D printing is used in giving provisionals or temp crowns during the tissue healing after implant placement. These provisionals help in attaining esthetics and function until a permanent abutment crown is fabricated.[36]

Stainless steel has been used to thread into the implant body so that a temporary crown could be fabricated. Stainless steel has proved to be cost effective, it has also reduced the lab time and showed a success rate of around 85%.[36]

Future Potential of 3D Printing in Dentistry:

3D printing technology has evolved significantly in recent decades; however, it still has certain limitations, particularly related to the materials used. A fundamental limitation of current 3D printing materials is their static nature, which restricts their ability to adapt to the dynamic oral environment and various internal and external stimuli. To overcome this challenge, 4D printing has been introduced, in which time is incorporated as an additional dimension into conventional 3D printing, enabling the use of smart materials that can respond to specific stimuli. Due to its adaptive properties, 4D printing demonstrates significant potential for applications in tissue reconstruction, implants, targeted drug delivery, diagnostic devices, and artificial substitutes that closely mimic human tissues.[11] Thus, shape-memory instruments or prosthetics produced using 4D printing technology could help prevent instrument fracture by adapting to root canal curvature during endodontic procedures. Additionally, dental implants with variable apical hardness may reduce the risk of nerve injury and sinus perforation. This approach also enables the development of biomaterials that conform to the contours of hard-tissue defects. Furthermore, 4D printing allows for the efficient production of prosthetic devices while utilizing low-viscosity materials.[10]

The prospects for 3D printing in dental prostheses production are very promising, with expectations that it will become increasingly prevalent in dentistry as technology continues to advance.[32] Future 3D printers will become more simplified in use, print faster at greater resolution, and manufacturers will refine processes to directly print orthodontic aligners, reducing environmental waste and speeding up manufacturing.[25]

Recent technological advancements in the digital workflow have increased interest in 3D printing for tissue regeneration, enabling 3D bioprinting to produce patient-specific scaffolds with high precision and accuracy. However, further research is required to optimize key aspects of the process, including the selection of appropriate biomaterials, imaging acquisition methods, and printing techniques.[40] Figure1.

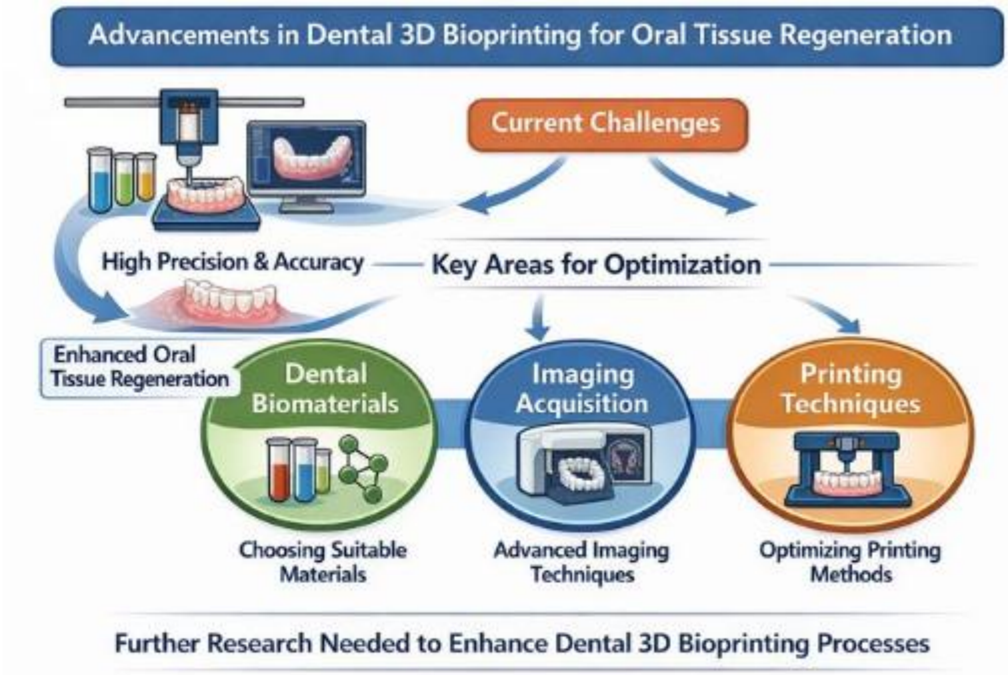

Fig1. Dental 3D Bioprinting Challenges

In addition, material innovations are being explored to further enhance the performance of dental prosthetics using this technology. Researchers are investigating their physical and biological properties to improve clinical outcomes. This includes incorporating hydroxyapatite into polymers to enhance osteoinductivity, applying surface modifications to metals to improve antibacterial properties and control degradation, and studying stem cell interactions with printed biomaterials to optimize bioactivity and promote early tissue reactions while reducing inflammation.[18] More recently, advances in 4D printing materials have led to the development of shape memory elastomers (SMEs), which exhibit dual- or multi-shape capabilities. These materials possess a permanent shape and a temporary shape, allowing them to reversibly change form in response to specific stimuli. Due to their low tensile strength and high elongation at break, SMEs can undergo significant deformation without rupturing, which may help reduce the risk of prosthetic fracture under functional or environmental stresses.[41]

Alongside advances in polymer and smart materials, metal 3D printing utilizes a laser to fuse metal powder particles layer by layer, enabling the fabrication of dental prostheses with superior strength compared to those made from polymers or resins. However, metal 3D printing is not suitable for all dental applications due to its high cost, technical complexity, and limited long-term clinical evidence; therefore, it remains an area under investigation.[32] Challenges include elevated expenses, requirement for innovative materials and technologies, high costs, material limitations, and post-processing requirements.[27] While 3D printing achieves clinically acceptable accuracy levels, it currently exhibits lower mechanical strength and stability compared to milling and traditional methods.[31]

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