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Printing the Future of Dentistry: Applications, Materials and Emerging Prospects of 3D Printing

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Abstract

Introduction. 3D printing is experiencing rapid growth, revolutionizing industries across the board. Encompassing various types, methods, and materials, 3D printing holds significant potential to contribute across multiple fields. From healthcare and dentistry to aerospace and fashion, this innovative technology is redefining how products are designed, manufactured, and customized. This technology enables the creation of three-dimensional objects from digital models. However, despite these advancements, many dental services have yet to fully adopt this modern innovation. Investigating the advancement of 3D printing technology in dentistry highlights its roles in modern dental innovation.

Review. 3D printing has evolved from 1980s prototypes to today's accessible technology, with seven types based on the printing process, according to the classification made by ASTM. Ongoing advancements in bioinks demonstrate significant promise for future bioprinting applications, integrating living cells and biomaterials. In dentistry, 3D printing technology enables the accelerated, highly precise, and customized fabrication of dental products, such as surgical guides, models, implants, restorations, and virtual surgical planning.

Conclusion. 3D printing currently offers significant advancements in precision, customization, and efficiency. While the technology has matured rapidly and presents diverse applications, continued integration and adoption within dental practices are essential to fully realize its potential and optimize patient care.

Keywords: 3D printing; Dentistry; Technology

1. Introduction

3D printing is a rapidly growing technology that makes it possible for us to make a 3D object originated from a digital model. The technology utilizes seven main techniques and is mainly applied across diverse industries, such as aerospace, automotive, healthcare, and electronics [1, 2]. These devices are essentially simple robotic systems that work with computer-aided design (CAD) software to build objects from the ground up [3]. Over the past 30 years, 3D printing has gained significant traction due to its potential for sustainable production and customized manufacturing [4].

3D printing technology has numerous applications in healthcare, including dentistry. Progress in 3D imaging and modeling has enhanced the role of 3D printing in dental practices. This technology has enabled dental laboratories to produce various dental products with greater speed, precision, and accuracy. Additionally, 3D printing makes it possible to replicate complex geometries that were previously unattainable using traditional methods [5].

In the medical and dental field, the evolution of this additive manufacturing technology has also transformed contemporary practice and it also has many applications enhancing the outcome of clinical practice [6]. This technology

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has revolutionized various aspects of dental care and practice, offering diverse benefits and holding great potential for the future of the dental industry [7]. In dentistry, 3D printing has various applications, including the production of surgical guides, physical models, dental or craniomaxillofacial implants, and restorations. 3D printing has also become a critical tool for virtual surgical planning. The growing significance of 3D printing in dentistry is due to advancements in 3D imaging and modeling technologies such as CBCT, intraoral scanning, and CAD/CAM [8].

The modern era has progressed, yet not all dental services have adapted to the innovations and technologies currently available. Many dental services today do not fully utilize the existing technological advancements, necessitating modernization. We are exploring 3D printing to implement modern technology in the field of dentistry. As 3D printing continues to evolve, it promises a future of improved dental care and more efficient clinical outcomes.

A comprehensive search of the literature was conducted using the following electronic databases: PubMed, Scopus, and Google Scholar. The search was limited to articles published between 2015 and 2024. The keywords used were "3D Printing", "Additive manufacturing", "Dentistry", and "Technology". Boolean operators (AND, OR) were applied to refine the search.

2. Review

The history of 3D printing can be divided into three distinct periods, reflecting significant technological advancements [4]. Early years (1981 - 1999) period is important for 3D printing technology development. In this era, Chuck Hull introduced the first patent for Stereolithography Apparatus (SLA) 3D printing. Afterwards, DTM Inc. created Selective Laser Sintering (SLS) and Stratasys patented Fused Deposition Modelling (FDM). That era was followed by 3D printing breakthroughs from 1999 to 2010, especially in the medical field. The breakthrough was marked by Wake Forest Institute for Regenerative Medicine because they successfully 3D printed a functional human bladder. The mechanism of printing was started with printing a synthetic scaffold, then coating it with the host's cells. No complication was found when the body accepted the organ. Unfortunately, the cost was high and desktop printers were not common. Those issues were solved in 2004 by the availability of free printer software and designs. Many patents on 3D printing technology expired in 2009, opening the door for numerous start-ups to produce dependable and reasonably priced open-source 3D printers.

In 2011, the current era of 3D printing began. In recent years, 3D printing technology has rapidly evolved. Since then, a large number of dependable and reasonably priced 3D printers and 3D printing software have become more widely available. The quick rise in processing power and speed by advancements in chip technology (Moore's Law), has reduced operating costs, improved printer accuracy, and simplified operations.

3. Types of Technology

Due to legal considerations, different manufacturers adopted unique acronyms to describe the same process, which can sometimes lead to confusion. To help clarify things, the American Society of Testing and Materials (ASTM) has grouped similar 3D printing processes into seven categories (ASTM F2792 12a).

3.1. Vat Photopolymerization

Vat photopolymerization involves additive manufacturing using a liquid photopolymer (resin) that is cured with UV light. Typically, support structures are required to stabilize parts during 3D printing. After the printing process, the next part is the removal of residual resin. Residual resin is removed by immersing the parts in an isopropyl alcohol (IPA) bath for several minutes. The supports are then trimmed away using clippers, following that trimming is stabilizing the physical properties. The technique for this stabilization stage is by baking the parts in a UV light box [4].

Two main configurations for vat photopolymerization are based on their exposure strategies: Stereolithography (SLA) and Digital Light Processing (DLP) [4]. SLA cures the resin layer by layer using photochemical processes, resulting in highly detailed and precise designs. Although the process produces smooth and accurate parts, it is time-consuming due to the laser beam following a specific path for each layer [9]. SLA printers support a wide range of materials, such as standard resins, engineering resins (flexible, tough, high-temperature, and durable), dental resins (for retainers and aligners), and castable resins (for custom jewelry) [4].

In contrast, DLP addresses SLA's slower printing speed by curing entire layers in a single flash of light. DLP uses a digital projector, which consists of square pixels, forming voxels. Larger voxels result in lower resolution (the objects look more pixelated), smaller ones make smoother objects with much better resolution [6].

3.2. Material extrusion / Fused Deposition Modeling (FDM) / Fused Filament Fabrication (FFF)

Material extrusion uses semisolid material. This material is extruded from a nozzle on the build plate layer by layer. [4] The layers will solidify upon cooling. A molecular bond is formed following the deposited heated filament on the previous layer [10]. Extrusion technique makes it possible to incorporate an additional nozzle. The function of this nozzle is to extrude soluble support material. After the printing process is finished, a solvent bath can be used to remove the support, so there is no need for manual clipping and/or sanding [4].

The technology works with thermoplastic materials [10], like acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Depending on the printer and the nozzle specification, the material could be nylon, composites, clay [4].

3.3. Directed energy deposition (DED)

Directed Energy Deposition (DED) involves fusing and depositing metal powder or wire onto a build plate using an electron or high-powered laser beam. This technique is similar to material extrusion but features a nozzle with multiple degrees of freedom, because it is mounted on an arm with a multi axis. So is the power source setup, allowing for movement across various angles. This flexibility allows material deposition at any angle to the build plate, making DED especially useful for repairing and maintaining structural components. This flexibility also allows DED to produce higher quality parts. Currently, metals and hybrid materials are commonly used with this technique. The main limitation of this technique is that a balance needs to be maintained between the speed and surface finish of the final product. Post-printing heat treatment may be necessary to improve the mechanical properties of the final product [1,4].

3.4. Powder bed fusion (PBF)

Powder Bed Fusion (PBF) is a manufacturing technique that uses laser, electron beam, or thermal energy to sinter or melt powdered materials to form objects. All PBF systems share three key components: a nozzle, housing the energy source for combining material; a build chamber for creating the part; and a feedstock system that supplies material for creating the part.

When using thermoplastic materials like plastic, nylon, or polyamide, additional supports are unnecessary because the unused powder (raw materials) serves as a cushion to support the part. However, when working with metal powders (raw materials) such as nickel alloys, stainless steel, cobalt, or titanium alloys, support structures are required to prevent warping or buckling due to the weight of the part and provide stability for overhanging features [4].

PBF methods are divided into five different groups. They are differentiated by the usage of power source.

- Selective Laser Sintering (SLS): SLS employs a high-temperature laser to selectively fuse powdered materials. These materials can range from ceramics and metals to polymers, making it particularly useful for producing high-density materials used in dental applications. However, the main drawback is that it requires large infrastructure to support the printing process [11].
- Direct Metal Laser Sintering (DMLS): DMLS uses a high-power laser beam to melt metal powder (20 micrometers diameter) and build the part with the same properties as the original material, without the need for binders or fluxing agents. In comparison to SLS, DMLS offers higher detail resolution since it utilizes thinner layers made possible by the smaller powder diameter. The materials commonly used include alloy steel, stainless steel, tool steel, aluminum, bronze, cobalt-chrome, and titanium [12].
- Selective Heat Sintering (SHS): SHS utilizes a thermal print head to process thermoplastic materials. By removing the need for a complex laser system, SHS offers a more cost-effective approach for producing prototype parts, making it an affordable solution for various applications [11].
- Selective Laser Melting (SLM): Unlike DMLS, which works with metal alloys, SLM uses single-element materials like titanium then fully melts metal powder to ensure uniform melting temperatures. The powder is melted by a high-powered fiber laser. Both SLM and DMLS require supporting structures for the print. The printing process is done by layering. SLM is commonly applied in aerospace and medical industries [4, 13].
- Electron Beam Melting (EBM): EBM utilizes a high-energy electron beam to melt metal powder. The process occurs in a vacuum, where the electron beam selectively scans and melts the powder layer by layer, creating a solid 3D object. After printing, the excess-unused powder is vacuumed out of the chamber, and it can be recycled for future builds, which helps reduce the overall operational costs [4, 13].
- Binder Jetting (BJ): In binder jetting, a layer of powder is spread across a platform, and the print head releases tiny droplets of binder onto the powder, which binds the material together to form a layer of the 3D object. After the first layer is printed, the powder bed is lowered to make room for the next layer, and this process repeats until the entire object is built. Once printing is complete, the object is left to cure and strengthen in the

remaining powder. After curing, the object is taken out of the powder bed, and any loose particles are blown away with compressed air [13]. BJ can print with a variety of materials, such as nylon, thermoplastics, and ceramics. One of the key benefits of this method is its ability to print in full color, with the 3D Systems ProJet CJP 60 printer series offering full CMYK color printing [4].

- Material Jetting (MJ): Also known as PolyJet, Material Jetting is similar to how traditional inkjet printers work, but instead of printing ink on paper, it builds a 3D object layer by layer. The printer head sprays hundreds of small droplets of photopolymer onto the platform, and each layer is hardened by UV light. As each layer cures, the build platform lowers, and the process continues until the object is fully formed. MJ requires a water-soluble support structure, which can be easily washed away in post-processing by using a water jet. It is known for its high precision, and since there's no need for post-curing, the final products have a smooth, clean finish [4, 13].
- Sheet Lamination (SL): Sheet lamination uses sheets of paper to create the 3D part. The printer typically uses A4-sized paper that's coated with a heat-sensitive adhesive. The process involves stacking layers of paper, and then a heated roller or press melts the adhesive to bond the layers together. This technology has the advantage of using regular printing paper as the raw material, making it much cheaper than other 3D printing methods. However, it does produce a significant amount of waste paper. Once the part is complete, it can be treated with epoxy to improve durability and give it a shiny finish [4].

Building upon the diverse techniques of 3D printing, the medical field has embraced these innovations to transform healthcare practices, with bioprinting emerging as a revolutionary advancement. Unlike traditional 3D printing methods used for industrial or mechanical applications, bioprinting integrates living cells and biomaterials to create intricate tissue structures that closely mimic natural tissues. This specialized application of 3D printing technology focuses on producing complex biological tissues for medical purposes, such as regenerating or replacing damaged tissues in the human body. Bioprinting provides significant advantages over the traditional regenerative method, offering high precise cell placement and high digital control of speed, resolution, cell concentration, drop volume and diameter of printed cell. Bioprinting enables the creation of three-dimensional tissue structures with predefined shapes and compositions. It precisely coordinates the deposition and cross-linking of bioink with the movement of a motorized platform. The bioink, which consists of biomaterials and/or living cells, is typically a hydrogel-based solution. It may contain several biomaterials and encapsulated cells to form tissue constructs. The development of bioprinted tissues solves the problem of organ donor shortage [13, 14].

Bioinks, which are essential for 3D bioprinting, consist of living cells and biomaterials that mimic the extracellular matrix (ECM) environment, thus facilitating cell adhesion, growth, and differentiation post-printing. The development of bioinks is critical as they must meet specific criteria distinct from conventional 3D printing materials. These criteria include maintaining physiological temperatures during printing, utilizing mild cross-linking or gelation conditions, and incorporating biocompatible and bioactive components that are non-toxic and adaptable to cellular modifications after printing. The requirement for printing at physiological temperatures is paramount to ensure cell viability and functionality. Bioinks must be formulated to remain stable and functional at these temperatures, which typically range from 37°C. Biocompatibility and bioactivity of bioinks are critical for ensuring that the printed constructs support cellular functions and tissue regeneration. Chen et al., 2021 emphasized that the incorporation of hyaluronic acid and proteins in hydrogels plays a significant role in tissue repair and regeneration, highlighting the need for bioinks to contain components that promote cell adhesion and growth [15]. The formulation of bioinks from natural biomaterials, as discussed by Benwood et al., further supports the notion that the mechanical, rheological, and cross-linking properties of bioinks must be optimized to enhance cytocompatibility and printability [16]. The integration of living cells with biomaterials that replicate the ECM environment is essential for successful tissue engineering applications. Future research should continue to focus on optimizing these parameters to enhance the functionality and applicability of bioinks in regenerative medicine. As shown in Figure 1, bioinks are created by combining cultured cells and various biocompatible materials. Bioinks can then be 3D bioprinted into functional tissue constructs for drug screening, disease modelling, and in vitro transplantation.

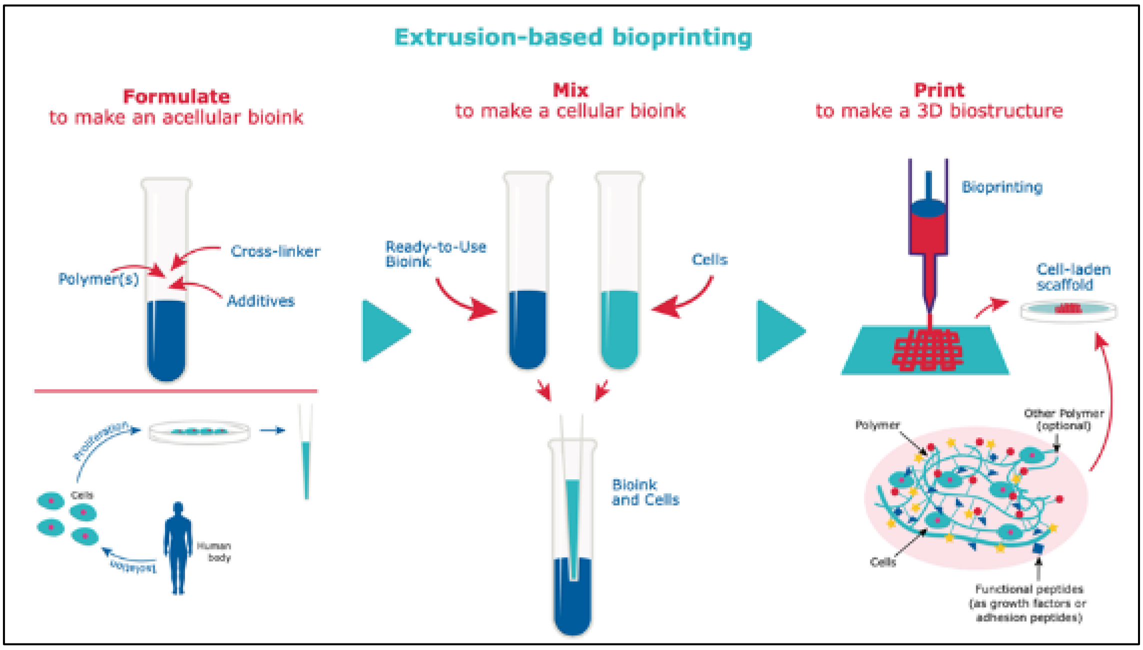

Figure 1 3D bioprinting is an additive manufacturing process that uses cells and biomaterials to print an object layer by layer on extrusion-based printer [17]

According to Yu et al, 2020, various materials can be utilized for bioink, including [18]:

Natural polymers such as alginate, chitosan, gelatin, collagen, silk, fibrinogen, agarose, hyaluronic acid, Matrigel, and bioceramics.

Synthetic polymers like polycaprolactone, polyethylene glycol, Pluronic F-127, polyvinyl alcohol, polylactic acid, and poly(lactic-co-glycolic) acid.

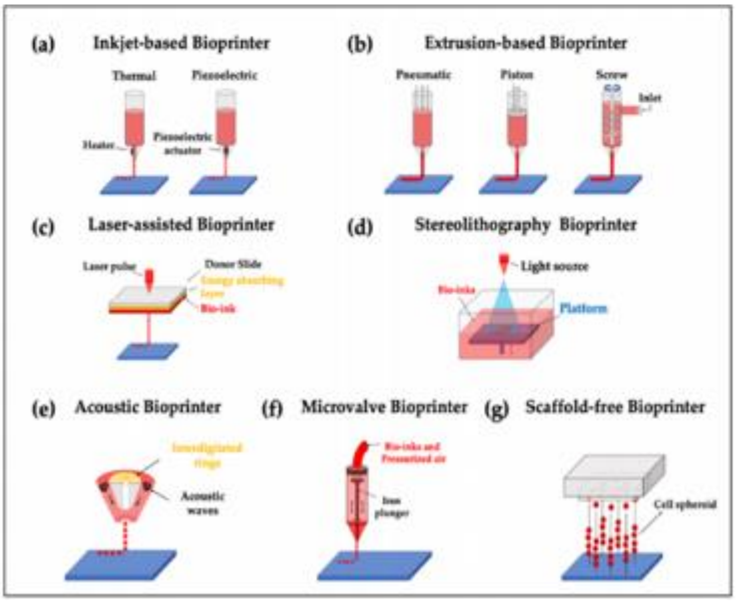

Figure 2 Different types of 3D bioprinters. (a) Inkjet (b) Extrusion-based bioprinters (c) Laser-assisted bioprinter; (d) Stereolithography-based bioprinter; (e) Acoustic and (f) Microvalve bioprinters; (g) Scaffold-free bioprinter [18]

4. Applications of 3D Printing in Dentistry

Three-dimensional printing has brought new applications along with the advancement of dental materials. Its versatile applications have provided more predictable clinical outcomes with precision and accuracy in many dental specialties. Applications of 3D printing in dentistry as seen on Table 1. In the following cases, the usage of 3D printing technology in the field of dentistry demonstrates its potential to revolutionize treatment planning and patient care.

A 30-year-old woman in good health came to the clinic hoping to replace her missing lower left first molar (#36), which had been extracted years earlier. Upon examination, both clinical and radiographic assessments revealed significant bone loss in the area, with deficiencies in both vertical and horizontal dimensions. To address this, the treatment plan included guided bone regeneration using a block graft, followed by the placement of a dental implant after four to five months, ultimately restoring the missing tooth with a single implant crown. To ensure precision, a 3D-printed model of the patient's jaw was created (Figure 3), allowing the surgical team to visualize the defect and design a customized xenograft block for reconstruction. This innovative approach transformed the pre-surgical planning process, making it faster, more accurate, and highly efficient. By enabling meticulous preparation and a tailored graft design, 3D printing technology streamlined the procedure and reduced the risk of post-surgical complications [19].

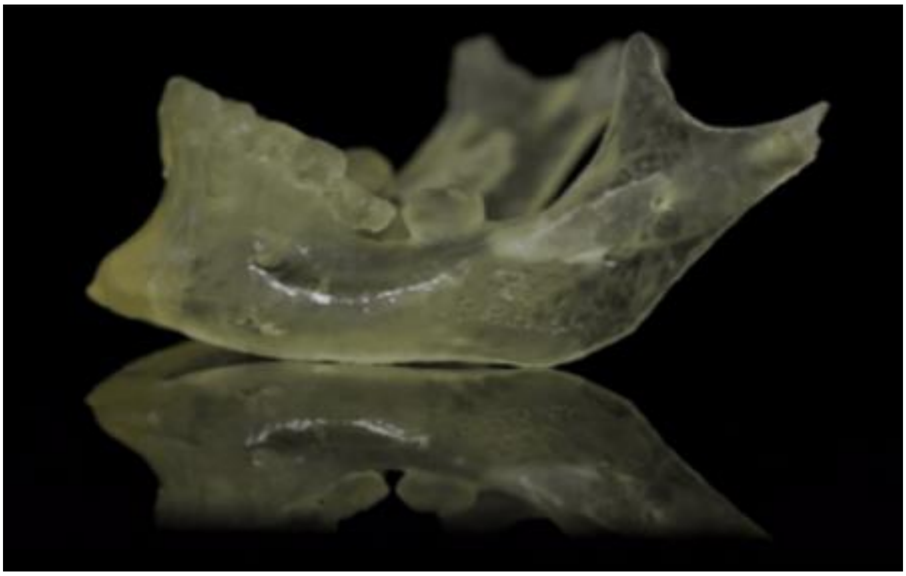

Figure 3 A 3D-printed mandibular jaw [19]

A 52-year-old man came to the Prosthodontics Department at Capital Medical University School of Stomatology, looking for a way to restore his upper teeth after losing his second premolar and molars three months earlier due to severe gum disease and bone loss. After discussing various treatment options, he decided on a maxillary removable partial denture (RPD), considering his health and financial situation. Using advanced intraoral scanning and 3D printing technology, the clinical team created a custom metal framework for the denture (Figure 4). The final result was a prosthesis that fit perfectly, with smooth, seamless contact between the framework, denture base, and surrounding tissues. Follow-up visits confirmed the denture was comfortable and stable, with no signs of tenderness or tilting. The use of 3D printing not only ensured high precision and accuracy but also dramatically reduced production time by up to 70%. This case highlights how 3D printing is revolutionizing clinical dentistry by offering faster, more efficient, and tailored solutions for patients [20].

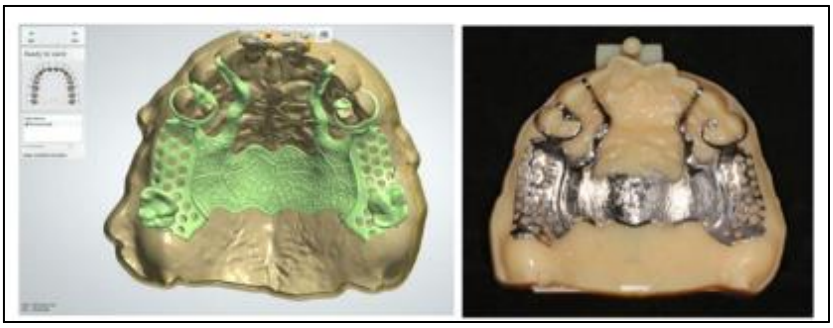

Figure 4 3D printed Kennedy Class I removable partial denture metal framework [20]

The integration of 3D printing with advanced antimicrobial monomers offers significant advantages in clinical dentistry. By incorporating positively charged quaternary ammonium groups into photocurable UDMA/GDMA resins, either through direct copolymerization or prepolymerization, 3D-printed dental materials gain enhanced antimicrobial properties. Using stereolithography for fabrication ensures high precision and structural integrity of printed objects, such as implant surgical guides. This approach not only provides accurate and customized dental solutions but also promotes infection control, reducing the risk of microbial contamination during surgical procedures. The combination of precision, efficiency, and antimicrobial benefits underscores the transformative potential of 3D printing in modern dental practices [21].

5. Conclusion

This literature review has demonstrated the remarkable evolution of 3D printing, from its foundational development to its current status as a pivotal technology within dentistry. The technology offers significant advancements in precision, customization, and efficiency, enabling the fabrication of diverse dental products and facilitating innovative clinical workflows. The rapid maturation of 3D printing has resulted in a wide array of applications, including surgical guides, prosthetics, and bioprinting, showcasing its versatility and transformative potential. However, the full realization of these benefits hinges on continued integration and adoption within dental practices. Overcoming barriers such as cost, training, and standardization will be crucial in ensuring that 3D printing's potential is fully harnessed to optimize patient care. Future research should focus on refining materials, validating clinical outcomes, and developing streamlined workflows to facilitate seamless integration into everyday dental practice. By addressing these challenges, the dental community can leverage 3D printing to revolutionize patient care and usher in a new era of personalized and efficient dentistry.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be be disclosed.

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