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Review Article

# REVOLUTIONIZING HEALTHCARE: A REVIEW OF 3D PRINTING IN DENTISTRY AND DRUG DELIVERY

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**ABSTRACT**

Three-dimensional (3D) printing will revolutionize healthcare by allowing personalized, efficient, and decentralized healthcare solutions. This assessment synthesizes current knowledge on the objectives, support, and limitations of 3D printing in dentistry and medicine distribution. 3D printing makes it easier to manufacture surgical instruments, diagnostic models, crowns, bridges, and bioprinted soft tissues in dentistry. It enables personalized, on demand formulations, such as oral polypills and microneedle array, together with a tunable release profile for drug delivery. Although promising, the field still faces several challenges, including technical obstacles, limited mechanical longevity of dental polymers, scalability issues in bioprinting, insufficient safety data, and the lack of uniform standards. Critics of research on how emerging technologies, such as Al and green components, can overcome existing obstacles, focusing on proposing realistic plans for future integration of 3D printing into global healthcare systems. Examples, such as the high success rates for 3D dental implant production and the Food and Drug Administration-approved 3D-printed drug Spritam, demonstrate the potential of 3D printing. The review also highlights the technology's ability to decentralize healthcare assistance, as demonstrated by clinics using desktop printers to manufacture low-cost dental appliances.

**Keywords:** Dentistry, Drug delivery, Personalized medicine, Surgical guides, Prosthetics, Fused deposition modeling, Stereolithography, Selective laser sintering, Digital light processing.

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## INTRODUCTION

The integration of three-dimensional (3D) printing into healthcare marks a significant shift toward personalized, efficient, and decentralized medical solutions. 3D printing makes it possible to manufacture patient-specific dental prosthesis and personalized medicine by overcoming the limitations of conventional manufacturing. The current digital evolution has particular value in solving the "one-size-fits-all" problem in dentistry and the rigidity of standard dosage in drug dispatch systems. With limited access to conventional medical aid groundwork, 3D printing's second ability to democratize healthcare transparency brings both social and economic advantages [1]. 3D printing, which was developed in the 1980s for industrial prototyping, has been rapidly evolving and is now a cornerstone of modern dentistry and pharmaceutical innovation. In dentistry, its grip is derived primarily from the manufacture of surgical instruments and diagnostic models, although it is progressive in its creation of durable crowns, bridges, and even bioprinted soft-tissue structures [2].

In parallel, drug delivery has moved from mass production paradigms toward tailored, on-demand formulations. To produce oral polypills and microneedle sites for transdermal drug delivery, together with the added benefit of a tunable release profile, tools such as amalgamation deposition molds (FDM) and stereolithography (SLA) are immediately applied [3,4]. Despite its promise, there are several significant obstacles preventing full adoption of 3D printing in clinical practice. Technical obstacles such as the mechanical durability of dental polymers and the scalability of bioprinting remain unsolved. Clinically, there is insufficient long-term safety data for 3D-printed implant and controlled-release medicines surrounding the practitioner. Controlling incompatibilities across zones is even more difficult, given the lack of uniform standards for 3D-printed medical devices around the world [5,6].

However, the clinical and administration practicalities of 3D-printed interventions are supported by mount indication. The success rates for 3D dental implant production are higher than 95% [7], while pharmaceutical developments such as Spritam, the first Food and Drug Administration (FDA)-approved 3D-printer, provide proof of concept for the nerve pathway [8]. Similarly, bioprinted corneal tissues developed alongside Newcastle University demonstrate the translational promise of combined biomaterials and linear manufacturing in regenerative medicine. 3D printing has demonstrated an unprecedented ability to decentralize healthcare assistance in a disadvantaged situation. For example, a clinic in Southeast Far East uses a desktop printer to manufacture low-cost denture and orthodontic appliances, drastically reducing costs and lead times compared to the import option [9]. Such localized objectives enhance the value of low-cost, scalable solutions in areas where sustained progress and policy conformity may enhance international health influence.

This review ultimately seeks to synthesize current knowledge on the applications, benefits, and limitations of 3D printing in dentistry and drug delivery. It explores how emerging technologies such as artificial intelligence and eco-friendly materials can address existing barriers, aiming to propose realistic strategies for the future integration of 3D printing into global healthcare systems.

## 3D PRINTING TECHNOLOGIES

Stereolithography (SLA), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Digital Light Processing (DLP), and bioprinting are among the key technologies that enable the production of customized dental appliances, such as prostheses and implants, with high precision. The innovations in dental applications are illustrated in Figure 1.

**SLA**

SLA is one of the earlier and mainly improved 3D printing techniques introduced during the 1980s [10]. It belongs to a broad class of photopolymerization wherein the selective movement of a watery photopolymer resin using a light source produces a strong composition layer by layer. This linear manufacturing method is widely acknowledged for its high resolution, accuracy, and facade coating, which makes it a better option for businesses such as healthcare, dentistry, automobile, aeronautics, and product design [11]. The core mechanism of SLA printing involves a vat filled with a liquid resin that reacts to ultraviolet (UV) light. A laser or virtual light projection traced a cross-section of the object onto the resin surface, hardened, or remedied. "Once a layer has been pulled around, the platform moves, allowing the next layer to remain pulled and pulled around by the superiority of the previous individual. The current system will repeat the entire 3D object form." The a Ask 8 of SLA is remarkable, with a tolerance often below 0.05 mm, which is suitable for applications where detail and precision are of paramount importance [12].

One of the major advantages of SLA is its ability to fabricate complex geometries that are challenging or impossible to achieve with traditional manufacturing methods. In terms of pharmaceutical objectives, SLA has made it easier to develop custom drug distribution frameworks, including multi-drug dose structures for oral use and polypills with precisely personalized release profiles. Experts have successfully printed layers of tablets integrating various antihypertensive agents using SLA despite unexpected photochemical chemical reactions between resins and medicines, highlighting the need for careful material selection [13].

Stereolithography (SLA) has shown great potential not only in fabricating customized medical devices but also in supporting the development of personalized medicine by enabling the production of patient specific dosage forms, implants, and tissue scaffolds. The systematic analysis of the SLA photopolymer formulation shows that the variation in resin chemistry, such as the molecular size of photopolymers and the type of filler, significantly influences printability and product quality. In the push for patient-specific therapy, current flexibility will be key. SLA has played a major role in the development of microfluidic devices and tissue technology structures in biotech. One's perfect resolution enables the assembly of capillary channels and hydrogel systems to facilitate cell growth and coordination. For instance, 3D hydrogels produced by SLA have been used to guide fibroblast conformity using protein-patterned surfaces to mimic native tissue architecture [14]. Further research confirms the time-stable biocompatibility of SLA-printed polymer, facilitating its use in bioanalytical tests [15].

Although they have several advantages, SLA is able to overcome certain limitations. These include the need for support systems during printing, post-processing requirements such as resin removal and UV hardening, as well as the potential toxicity or instability of a couple of photopolymer elements. The challenges for widespread use of medical devices and medicines continue to be with regard to the speed of printing and the portability of safe biocompatible resins [16].

**Fused deposition modeling (FDM)**

Fused deposition modeling (FDM) is one of the most widely used 3D printing systems due to its simplicity, cost-effectiveness, and versatility. FDM works by heating a thermoplastic fibril to a semiliquid state and then extruding it layer by layer through a nozzle to form a 3D object on a 3D printer [17,18]. This process is governed by a digital design file, which guides the nozzle's path and extrusion rate to replicate the model accurately.

SLS, a powerful 3D printing technique that uses a high-octane laser to mix powdered materials layer by layer into solid parts. Their main advantage lies in their material flexibility, which allows them to process a wide range of natural elements, including polymers such as nylon, metals, ceramics, and complex [19]. The current technology makes it possible to manufacture custom-made, high-strength, and lightweight components in many sectors, especially in dentistry for products such as dentures and dental casts. SLS has a high value for production parts, together with excellent mechanical robustness, ecological resistance, and all-round detail resolution without the need for support compositions during printing. Nevertheless, the technology achieves a high degree of efficiency, namely the high initial investment in equipment and the high cost of substances, which may restrict its use to a small, alternatively budget-conscious user.

**SLS**

SLS, a 3D printing innovation using a high-octane laser to mix powdered thermoplastic elements layer by layer within a solid object. Unlike SLA, which uses flowing resin with UV lasers to produce a smooth, high-precision model, SLS relies on heat and powder fusion to produce a robust and intricate geometry that does not require the support of aid organizations. This makes SLS suitable for functional prototypes, industrial parts, and custom manufacturing, where mechanical resilience is of paramount importance. As 3D printing tools continue to develop, SLA and SLS are redefining a path for innovation in fields such as healthcare, automobile, and aerospace [20].

**Digital light processing (DLP)**

Electronic light handling (DLP) is a high-tech 3D printing tool that uses UV projectors to spread light-sensitive resin layer by layer, producing fine details and smooth surfaces with extreme precision. DLP is known for its quick creation speed and high accuracy and is particularly efficient in producing complex geometry using zirconium oxide, alumina, and hydroxyapatite. This makes it a perfect solution for dental design, including surgical guides, orthodontic aligners, dental models, and custom implant. DLP has the ability to transform the workflow of dental manufacturing, guaranteeing quicker turnaround times and better long-term results by offering improved biocompatibility, clarity,

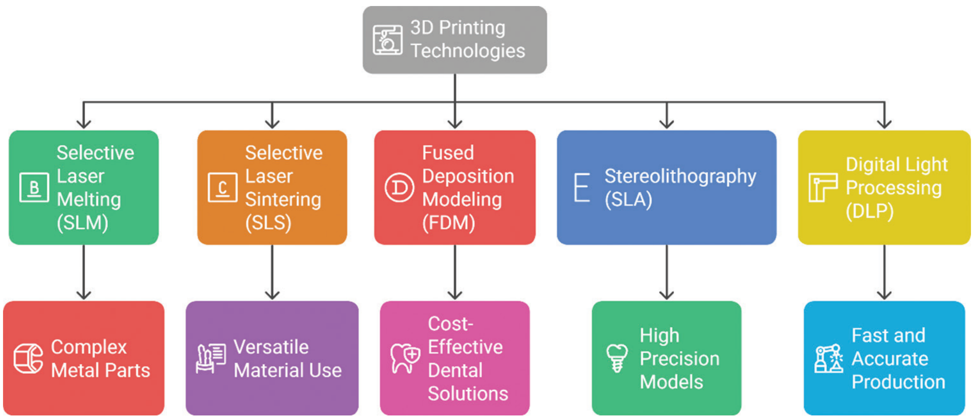


**Fig. 1: 3D printing technologies in dentistry**

and customization compared to conventional methods. Its simplified system and high-quality results continue to inspire creativity in the field of digital dentistry [21,22].

**SLS**

SLS is a modern 3D printing tool which can produce intricate and robust components by sintering powdered elements with a high-energy laser. The SLS is designed to suit a wide range of natural materials, such as polymers, metallic elements, ceramics, and composites, which makes it extremely suited to personalized design, including in the plains the advantages of dentistry and tissue technology. Its ability to fabricate lightweight and high-resolution parts like dental molds and dentures adds to its appeal in medical and industrial domains. However, the advanced nature of SLS comes with a trade-off, as the technology's high equipment and material costs can pose barriers to widespread use [23].

## APPLICATION OF 3D PRINTING TECHNOLOGY IN DENTISTRY

3D printing technology is revolutionizing dentistry, offering innovative solutions to the problems of the involved alveolar consonants, from implant and prosthesis to orthodontics and tissue regrowth. As oral health remains a key factor for general happiness, traditional methods often struggle with severe tissue damage that otherwise requires highly precise adaptation [24,25]. 3D printing, a cutting-edge tool, enables the creation of patient-specific dental appliances, together with the peculiarity of its design. The functions of the duration of the dental implant, custom-made prosthetics, visible aligners for orthodontics, and advanced maxillofacial surgical procedures significantly advanced consequences and long-term relaxation. The versatility of 3D printing materials, including biocompatible resins and ceramics, as illustrated in Fig. 2, enables long-term, esthetic, and functional dental restoration [26].

The existing tools also simplify the workflow, reduce production times, and assist minimally invasive procedures, thus providing a cost-effective and simplified replacement for mandatory systems. Together with its own expertise in integrating virtual scans for quick prototyping, 3D printing, modifying dental techniques, and personalized repairs that enhance the clarity of the analysis, systematic planning, and execution [19]. As the dental industry persists in adopting such revolutionary tools, it is paving the way for the development of regenerative dentistry and the introduction of green technologies, as well as 3D printing as an indispensable tool for the modern oral health system [24].

## THE APPLICATION OF 3D PRINTING TECHNOLOGY IN MEDICAL

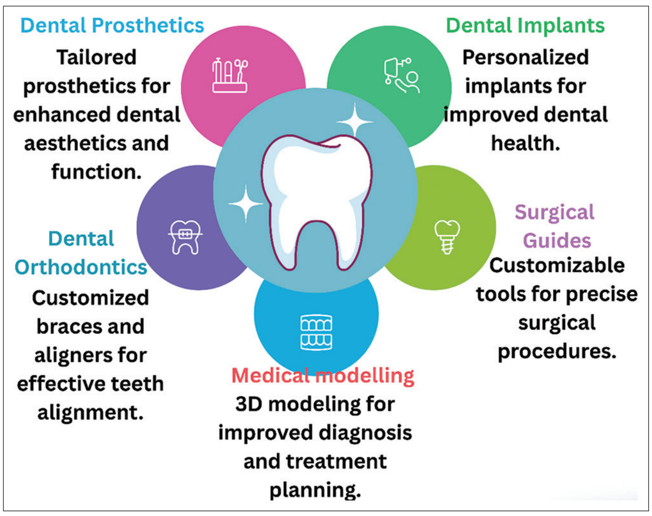


**Fig. 2: Current applications of three-dimensional printing technology in dentistry**

## DEVICES

**Surgical guides**

Surgical guides are custom-made dental appliances that play an essential role in ensuring precise and precise implant placement during oral surgery. Such a sheath is designed to fit beyond the permanent dentition, highlighting the hole where the surgical drill is positioned in accordance with the correct location, angle, and depth. This clarity will make it easier to predict and achieve implant procedures, minimize risks, and enhance the long-term effects [27,28].

The surgical usher transforms dental implantology by integrating computerized precision with clinical execution, thus ensuring minimally invasive and highly precise methods. In the current study, the workflow starts with an intraoral scan using the Cerec AC® framework of Sirona Dentsply, Germany, which digitizes the anatomic model and generates an SSI-language projection for digital organization of the implant's second optimum situation. The computerized facts were then translated into a DD-language file enabling the seamless import of the Sirona Dentsply software for surgical usher design. The design phase was methodically structured: First, the ridge boundaries and guide length were meticulously mapped to align with the patient's alveolar anatomy (Fig. 3a), ensuring a snug fit and stability. Next, the ring's position and size – critical for guiding the drill during implant placement – were calibrated to match the implant's diameter and angulation (Fig. 3b). Finally, a 3D projection of the surgical guide was rendered (Fig. 3c), providing a comprehensive preview for verification. Once approved, the guide was 3D-printed, translating the virtual

**Fig. 3: (a) Definition of the limits of the surgical guide. (b) Ring position. (c) Projection of the final surgical guide Reprinted with permission from Mukai *et al.* [29]**

blueprint into a tangible, patient-specific tool [29].

These guides act as a bridge between pre-operative planning and surgical execution, allowing the dentist to transfer a computerized design directly into the patient's oral cavity. By capitalizing on cone beam computed tomography (CBCT) scans to obtain detailed 3D alveolar bone statistics, a clinician can avoid key organs such as nervousness and fistula and minimize injury and post-operative complications [30]. Compared with conventional surgical techniques, which regularly include invasive flap surgery and freehand drilling, 3D-printed surgical instruments simplify the system, reducing surgical time by up to 50%, removing the need for a number of instruments, and improving sub-millimeter accuracy. This accuracy not only maintains the original dental tissues but also ensures longer implant stability by stopping nerve damage and bone heating [30].

The clinical acceptance of such ushers possesses billow, and examinations confirm their role in improving patient outcomes: Reduce pain, rapid recovery, and predictable outcomes. For instance, the integration of the SSI/DXD lingo protocol with the inLab 15 software allows real-time adjustment of the usher second design, allowing last-minute anatomic variation. Moreover, 3D printed ushers currently support complex maxillofacial surgeries, such as full arch reconstruction, by combining CBCT data with intraoral scans for single accuracy. Each design element, from the ridge function to the ring alignment, is optimized so that the implant integrates perfectly with the second biomechanics and solidifies 3D-printed surgical guides as essential instruments of modern, patient-centered dentistry [31].

**Medical modeling**

"Medical modeling, one of the earlier uses of 3D printing in surgery, revolutionizes pre-operative planning by facilitating the creation of anatomical models." These models are built using volumetric image statistics derived from progressive image modality, that is, CBCT, otherwise CT scan, which is becoming more and more common in dental procedures and hospitals. CBCT, through improved diagnosis and treatment organization, has significantly transformed implant dentistry and endodontics [32]. Using these image methods, a detailed replica of persevering anatomy, such as the jaw, can be produced using a 3D printer. The current technology enables a surgeon to carefully study complex or unfamiliar anatomy and plan a surgical approach with increased precision [33,34].

The incorporation of 3D printed surgical instruments further simplifies surgical procedures by providing a drilling or a template adapted to the patient's anatomy. Such measures facilitate faster surgical procedures, minimize invasiveness, and enhance predictability. For instance, Fig. 4 shows the use of a resin-printed model and a bore usher for concurrently packed low arch implant rehabilitation and mandibular reconstruction The process involves using an implant drill guide over a 3D-printed model (Fig. 4a), bending an osteosynthesis plate on a sterilized medical model (Fig. 4b), and placing the plate accurately during surgery (Fig. 4c) [35].

Although it has its own groundbreaking abilities, healthcare modeling imposes restrictions related to image artifacts caused by metallic organizations admiring restoration otherwise implant, which can affect accuracy. However, these errors are regularly clinically irrelevant to most surgical uses. Moreover, the choice of substances for the printing clinical model is crucial; sterilizable options such as nylon are particularly advantageous for use in the operating suite [36].

**Orthodontics**

Orthodontics, a branch of dentistry focusing on diagnosing and correcting misaligned dentition and jaws, has made significant progress alongside the integration of 3D printing technology. Traditional orthodontic appliances such as models, aligners, and retainers were manufactured by manual processes such as hot pressing, which frequently sought active and precise prerequisites for orthodontic treatment. However, 3D printing has advanced this process by enabling the creation of highly accurate, custom-made, and multi-functional devices that are personalized to human needs [37,38].

For instance, a persistent diagnosis with a tongue-thrusting habit, shallow overjet, and overbite requires a Transpalatal arch (TPA) for vertical molar height, direct and palatal parallel bars toward correct tongue position. The scan of the cast produced a digital model of the dentition, and the 3D-printing of the TPA was planned, together with a modified palatal irritant for habit correction and a vertical handle. Soldering for Adaptability was the irritating agent. Once attached, the 3D-printed TPA is able to restrict tongue thrust immediately (Fig. 5a-d). This scenario shows how 3D printing enhances accuracy, performance, and customization of orthodontic treatment [38].

Although 3D-printed invisible orthodontic appliances provide advantages similar to a smooth outer surface and fewer community attachments compared to conventional dental appliances, problems persist with underprivileged durability and biocompatibility. To overcome these difficulties, essential research has been undertaken on advanced high-tech elements. For instance, a modified hydroxyapatite occlusal composite having improved mechanical properties and antimicrobial properties has been applied to the filler and polymer matrix. Fig. 6 shows the use of a thermoformed transport template in the duo bonding protocol, demonstrating the development of material practice.

The development of 3D printing components for orthodontic appliances with excellent biocompatibility, stability, and safety for long-term use in the oral environment remains the main focus of research. The above innovations seek to meet the increasing demand for robust and patient-friendly orthodontic solutions while ensuring correctness and comfort.

**Dental implants**

Dental implants are medical devices surgically inserted into the jawbone to replace missing teeth, providing support for artificial teeth such as crowns, bridges, or dentures [41]. These implants, typically made of titanium or ceramic, appear to be synthetic roots, providing a stable base for prosthetic dentition. The procedure involves several procedures, including osseointegration, where the lower jaw integrates into the implant, followed by abutments and finally restoration. In view of their longevity and ability to enhance chewing function and oral health as a whole, dental implants are preferred over dentures. Implants can end their lives properly, enhancing the aesthetic as well as the functional aspects of dental health [42].

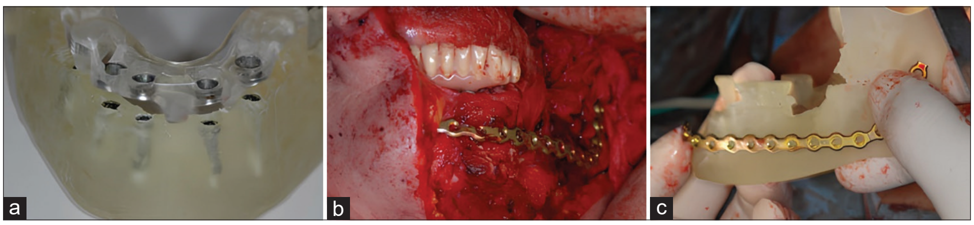


**Fig. 4: (a) Implant drill guide over the 3D printed model. (b) Bending the osteosynthesis plate on the sterilised medical model. (c) Plate in place.**

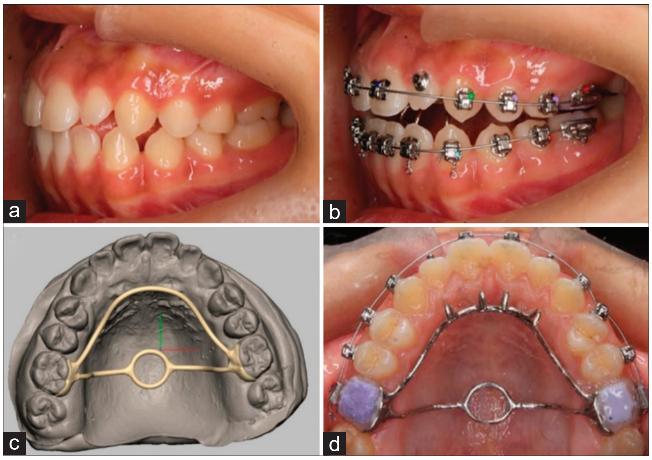


**Fig. 5: (a), followed by the disappearance of this habit after wearing the three-dimensional (3D) Transpalatal arch (TPA) (b). The digital design of this custom-made appliance is shown in (c), highlighting the precision of CAD/CAM technology. Finally, (d) depicts the fabricated 3D TPA with palatal thorns bonded to teeth, demonstrating how this innovative approach effectively addresses oral myofunctional disorders like tongue thrusting through advanced orthodontic solutions. Reprinted with permission from MDPI [39]**

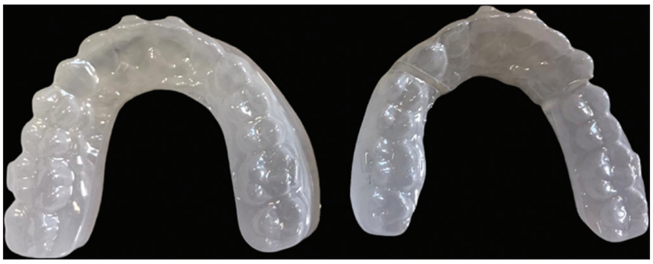

**Fig. 6: Thermoformed transfer templates used in two bonding protocols to enhance orthodontic treatment precision and efficiency. Reprinted with permission from MDPI [40].**

Three-dimensional (3D) printing technology has revolutionized various fields of dentistry, including implantology, enabling the creation of patient-specific treatments. The evolution of the 3D-printed double-root implant, which aims at mimicking the natural tooth structure and achieving sustained effects compared to the conventional single-root implant, is one creative strategy. Chung *et al*., the possibility of 3D-printed double-root implant compared to single-root implant is investigated in systematic reports. Preclinical evaluation of Ti 6Al 4V powder was conducted to assess its suitability for fabricating single and double root dental implants. The clinical and radiographic evaluation of the osseointegration of the fetus showed victorious osseointegration free of peri-implant inflammation, similar to inflammation, bleeding, swelling, or ulcer. As shown in Fig. 7 of Chung *et al.* To facilitate plaque management and measurement of implant durability, a protective cap was removed a pair of weeks after implant placement. This study focused on marginal bone changes, implant stability, micro-CT, and histological analyses. The findings indicated comparable stability and bone remodeling for both implant types, although some bone loss was noted in the furcation area of double-root implants, suggesting the need for further investigation before clinical implementation [43].

## THE APPLICATION OF 3D PRINTING TECHNOLOGY IN DRUG DELIVERY

### Tailored drug release profiles

Tailored drug release profiles refer to the customization of drug delivery systems to achieve specific pharmacokinetic outcomes, optimizing therapeutic efficacy and patient adherence. To limit the amount, duration, and location of release of the medicinal product, the profiles above are designed by adjusting the composition components and dosage form architecture. For instance, polymer admirers Eudragit® RL PO and RS PO can be mixed in a change ratio within a hot melt bulge to modulate release kinetics-higher RL PO satisfied accelerate release during RS PO, which lasts more than 12 h [44]. The modular dose styles make it possible to independently regulate the dose and release properties by uniting standardized and custom-made fractional monetary units, for instance, six distinct release profiles from only three faculties without changing the shape of the dose [45]. Suspended release systems, identical to polymer matrix or core/shell fiber frameworks, maintain a safe plasma concentration by gradually removing the medication, decreasing dose frequency, and side effects. For a drug with narrow curative windows or short half-lives, ensuring efficacy while minimizing toxicity. Sophisticated manufacturing methods, including 3D printing and melt processing, make it possible to produce a personalized design that is compatible with long-term requirements [46].

Govender *et al*. [45] presented a modular product design concept for independent garment manufacturers to solve the problem of personalized therapeutics (Fig. 8). The examiner recommended a 3D-printed hard oral dose shape consisting of two interchangeable faculty (100 $mm^3$ each) assemble within a fixed size unit of measurement (200 $mm^3$). The individual faculties have spatially separated dose and release control functions: A melt-extruded core containing 40% wt/w metoprolol succinate in a hydrophilic PEG1500/VA64 matrix acts as a reservoir, while the outer submodular components – polylactic acid (PA) cup and polyvinyl acetate (PVA) lids – govern the release dynamics. For instance, faculties with no eyelids (MV1) were able to release rapidly; water-soluble PVA eyelids (MV2) had a slowdown phase, and water-insoluble PLA eyelids (MV3) had a delayed initial hydration. As an amalgamated deposition mold (FDM), the squad shows that two faculties unite (e.g. MV1+MV 3) produce predictable, combined release profiles e.g., biphasic alternatively released. Unlikely, only three faculty discrepancies produce six distinct release profiles, highlighting the functionality of the reconfigurable assembly.. The study will focus on the power of 3D printing to unify product design, manufacturing, and patient-specific requirements, bringing together speculative mass customization principles with pharmaceutical intent.

Recent advances in 3D printing tools have made it possible to develop a personalized delivery system, especially in pediatric applications. The study by Tabriz *et al*. 48] demonstrates the manufacture of chewable pediatric ibuprofen (IBU) tablets using 3D Microextrusion Printing, a technique that eliminates the demand for filament pre-processing, unlike FDM or SLS systems. The current Microextrusion technique enables the direct deposit of a mixture of drugs and polymers and the production of a tablet with high reproducibility and a smooth surface. To disassemble the acrimonious taste of IBU and couturier release profile, a polymer identical to Eudragit EPO, Soluplus, and PVP-VA64 was used. The thermal and systematic analysis, including differential scanning calorimetry and X-ray powder diffraction, confirms that IBU transforms into an amorphous declaration after printing, with a strong preference for improved solubility. Furthermore, Raman spectroscopy showed strong hydrogen bonding between IBU and polymer, allowing simultaneous taste of the cover and control of release. In particular, tablet printing together with low infill density exhibits faster drug release due to an augmented facade area. The importance of polymer selection for achieving a custom release profile has been highlighted in dissolution studies on pH levels. Fig. 9 of the Examined Sightwise Capture of this Dissolution Interaction illustrates how the method of filling and polymer type significantly influences release rates close to different pH conditions.

The current research focuses on the manufacture of personalized pediatric chewable IBU tablets using 3D printing, donation advantages such as lead powder bulge without pre-processing, and the ability

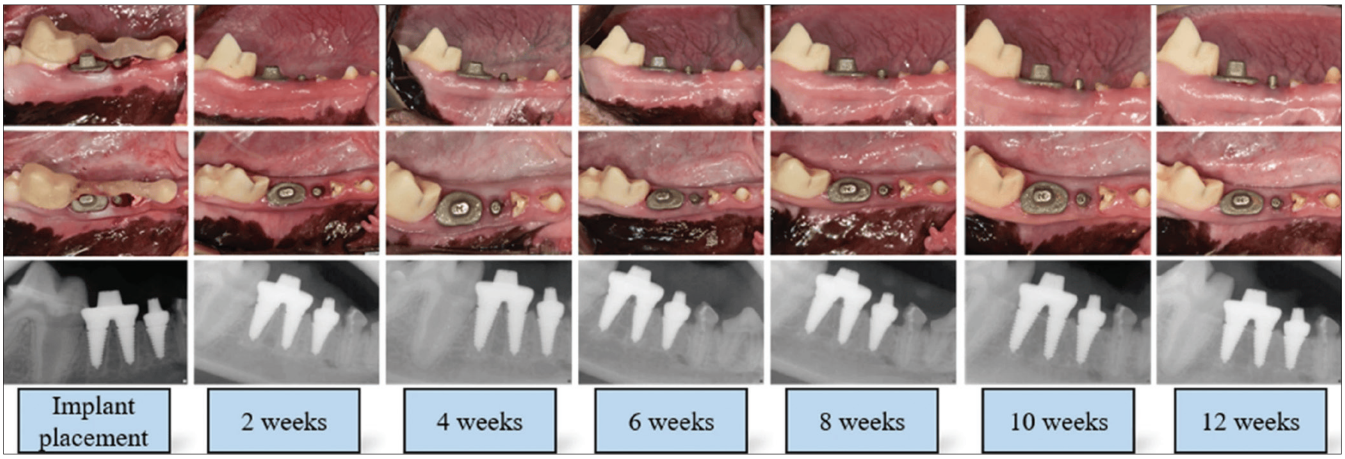


**Fig. 7: Clinical and radiographic photographs of single- and double-root 3D-printed dental implants, captured at the time of placement and at 2, 4, 6-, 8-, 10-, and 12-weeks post-implantation. Protective caps were removed two weeks after placement to assess plaque control and implant stability. The images show no signs of peri-implant inflammation, indicating successful integration and healing of the implants. Reprinted with permission from Springer Nature [20]**

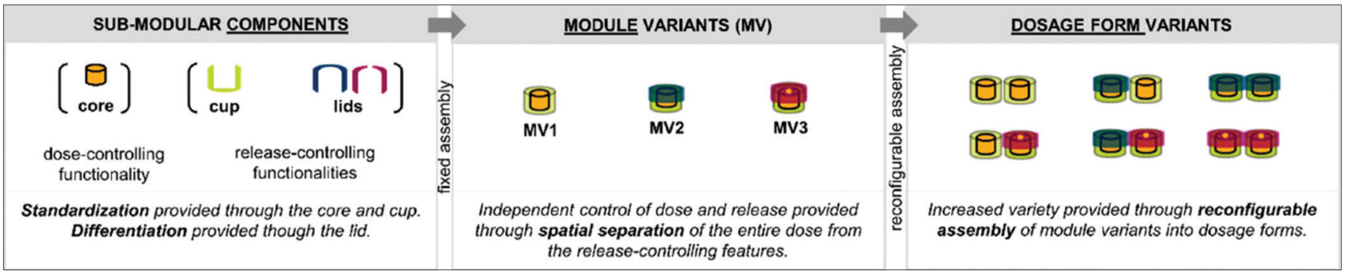


**Fig. 8: Modular three-dimensional printed dosage form. Reprinted with permission from MDPI [45]**

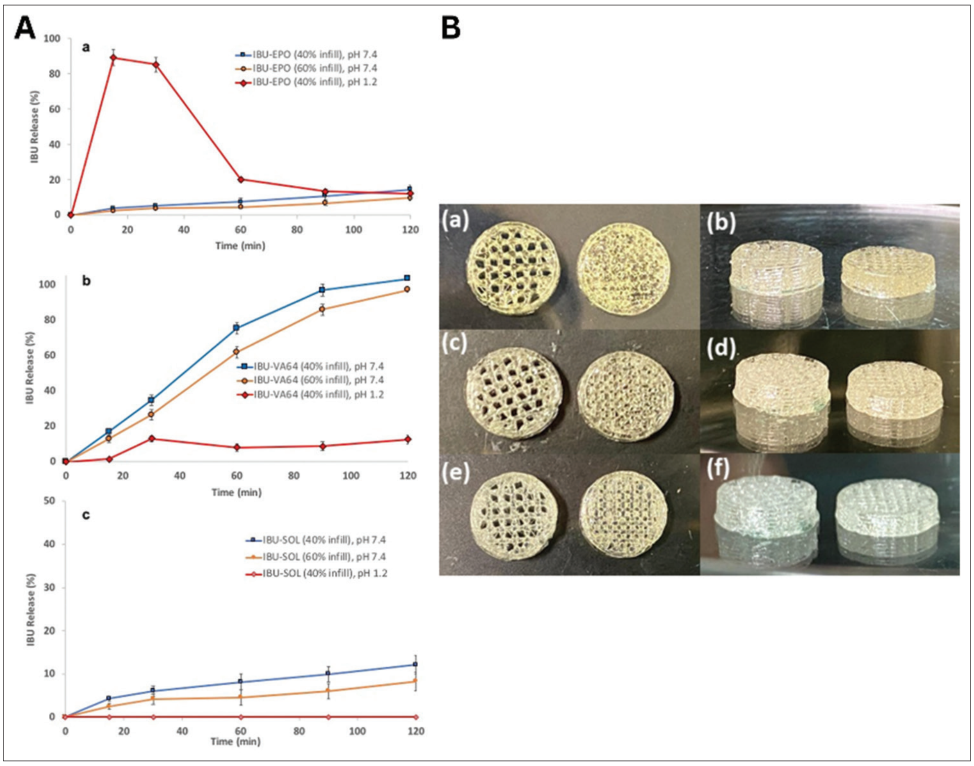


**Fig. 9: (A) (a-c) Dissolution profiles of 3D printed ibuprofen tablets composed of Eudragit EPO (ibuprofen [IBU]-EPO), VA64 (IBU-VA64), and Soluplus (IBU-SOL) at two infill densities (40% and 60%), showing drug release behaviors in simulated gastric (pH 1.2) and intestinal (pH 7.4) fluids. Lower infill densities generally resulted in faster drug release due to increased surface area. (B) (a-f) Optical images of corresponding 3D printed tablets illustrating shape fidelity and surface quality for EPO/IBU, Soluplus/IBU, and VA64/IBU formulations at 40% and 60% infill density; images include top and side views for each polymer type.© 2022 The Authors. Published by Elsevier B.V. [47]**

to control release of the medicine through the design and polymer choice. Three polymers were used to bond an IBU-loaded formulation with 40% drug satisfaction and to print within a tablet approximately 40% and 60% infill density. The morphology and reproducibility of the tablet were verified by optical images (Fig. 9B), which confirm the ability of the microextrusion technique to produce precise and uniform tablets. Dissolution studies have shown that polymer type and filling density have influenced the release of the medicinal product. The EPO-based tablet exhibits rapid dissolution at a pH of 1.2 but a narrow release at impersonal conditions (pH 7.4), in line with its recognized solubility. The VA64-based tablet achieved control release with improved solubility in alkalines and a longer supersaturation due to their crystallization-inhibitory properties. Slow release of SOL-based tablets due to H-bonding weakening polymer hydrophilicity. As shown in Fig. 9A, a tablet containing 40% of fill density rather than 60% concentrates the drug faster and emphasizes the covering region as a key element in the dynamics of release [47].

**Polypills/multi-drug combinations**

The development of polypills, which combine a number of medicines into an individual, customizable dosage structure, is revolutionizing the delivery of medicines. The present method allows a personalized dose adapted to the needs of the individual, tolerant, that is, elements such as era, metamorphosis, and comorbidities, thus reducing side effects and advancing attachment. For instance, scientists from the University of Nottingham used the Multi-Material InkJet 3D printer to produce polypills with a personalized release profile, which could react to UV light for precise drug distribution [48]. Further development of polypills containing up to 6 drugs (e.g., paracetamol and aspirin) in a separate layer, an individual with personalized release dynamics. The FDA-approved 3D-printing tablet, Spritam, symbolizes the speed of dissolution and precise dosage [49]. In addition, a unite blend deposition mold (FDM) with a thaw cast allows the body separation of incompatible drugs (e.g., aspirin and simvastatin) in a single pill which enhances its durability and drug loading capacity. These innovations simplify medication regimens, reduce administration errors, and improve clinical outcomes, particularly for chronic conditions like cardiovascular disease [50].

In a study by Zhang *et al*. [51] to produce a two-layer combi-pill using a new dual-technique 3D printing method, semi-solid syringe bulge (SSE) and blend deposition modeling (FDM), a new two-technique 3D printing method was applied. Tranexamic acid (TXA), a water soluble, rapid release drug, and indomethacin (IND), a poorly soluble, sustained release drug, were selected to evaluate the formulation performance under different solubility and release conditions. The TXA layer was printed using SSE due to its room temperature process, which is suitable for heat-sensitive APIs, while the IND layer was printed using FDM for its robust architectural qualities. The result polypill has successfully achieved distinct release profiles-immediate for TXA and widening for IND-which makes it perfect for scenarios requiring rapid anti-bleeding action followed by sustained anti-inflammatory effects, such as injury awareness. Moreover, the analysis confirms the durability of the drug-polymer matrix and the mechanical robustness

**Table 1: Summary of challenges and proposed solutions**

| Challenge | Field | Proposed solutions |
|---|---|---|
| Accuracy and precision | Dentistry | Use high-quality materials, advanced software for design and printing, and regular calibration of three-dimensional printers. |
| Material compatibility | Dentistry and drug delivery | Develop biocompatible, durable materials; explore new materials that mimic natural textures and appearances. |
| Regulatory frameworks | Dentistry and drug delivery | Increase collaboration between professionals and regulatory agencies to establish clear guidelines. |
| Cost barriers | Dentistry | Promote wider adoption to reduce costs; invest in research to improve cost-effectiveness. |
| Training and knowledge gaps | Dentistry | Implement comprehensive education programs for dental professionals on additive manufacturing techniques. |
| Post-processing time | Dentistry | Optimize prefabrication and post-processing methods to reduce labor intensity. |
| Personalized medicine challenges | Drug delivery | Enhance CAD software capabilities for complex designs; develop robust systems for on-demand manufacturing. |
| Bioprinting limitations | Dentistry | Advance research in bioinks and patient-specific cell applications to enable living tissue fabrication. |

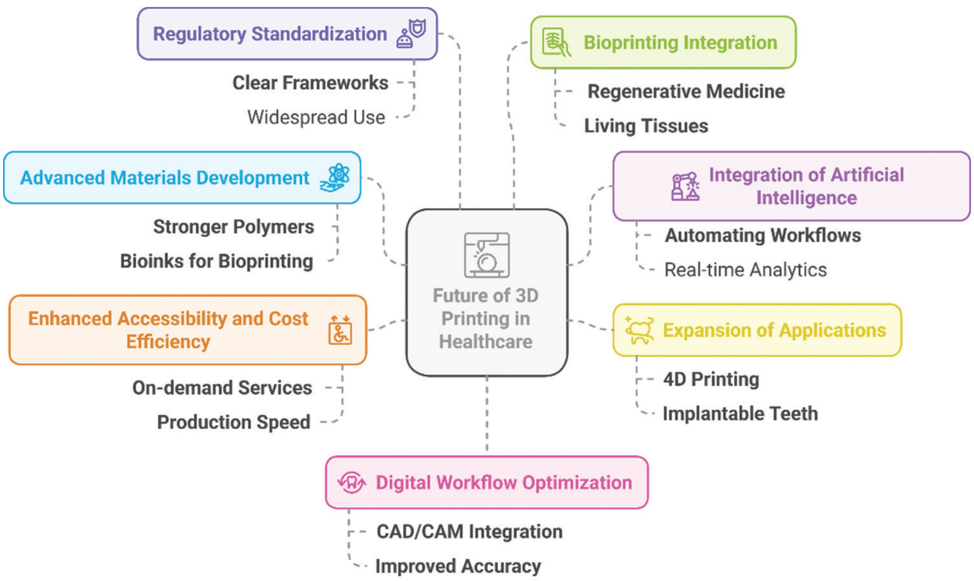


**Fig. 10: Future directions of three-dimensional printing in healthcare**

by the crumbling test. These results demonstrate the ability of 3D printing of multi-materials in combination with programmed release of medicines, including the approach to personalized medicine at the forefront of attention.

**FUTURE DIRECTIONS**

3D printing is transforming both dentistry and drug delivery with its ability to create highly customized, precise, and efficient medical and dental solutions. As the technology evolves, future directions will focus on integrating smarter materials, automation, and patient-specific customization. In dentistry, 3D printing will increasingly support the fabrication of patient-specific prosthetics, implants, aligners, and surgical guides [52]. Advanced integration of AI and imaging systems will allow real-time design and printing of restorations directly in clinics, drastically reducing chairside time and enhancing patient comfort [7]. Innovations like 4D printing – materials that change shape over time – could further expand clinical applications in orthodontics and soft-tissue regeneration [1]. Innovations like 4D printing – materials that change shape over time – could further expand clinical applications in orthodontics and soft-tissue regeneration (Fig. 10).

For drug delivery, 3D printing enables the creation of "printlets" – tablets with customized drug doses, release profiles, and shapes – tailored to individual patients' needs. Future research is focusing on printable biomaterials that can release multiple drugs at specific times or react to physiological changes in the body [53]. In addition, implantable devices that release medication over time or respond to environmental cues are a promising avenue for chronic disease management. Combining both fields, researchers are exploring 3D-printed oral appliances that deliver drugs directly within the mouth, such as antimicrobial agents for gum disease or slow-release fluoride for cavities [1]. These multifunctional devices promise to streamline both dental therapy and drug administration. The huddle possibilities and their solutions have been listed in Table 1

**CONCLUSION**

3D printing is a groundbreaking force in contemporary medical care, especially in the field of dentistry and drug delivery, by facilitating personalized, efficient, and decentralized healthcare solutions. The development of patient-specific dental prosthesis, personalized medicines, and on-demand clinical devices demonstrates the ability of innovation to overcome the limitations of compulsory production. Regardless of the existing technical impediments, such as the mechanical durability of dental polymer and the scalability of bioprinting, the clinical and administrative practicability of 3D-printing interventions is supported by the Mount Sign, including the high success rates of 3D dental implant manufacturing and the pharmaceutical progress of FDA-approved Spritam. 3D printing's competence to decentralize medical assistance aid in deprived conditions emphasizes its potential to enhance international health dominance through low-cost, scalable repairs. 3D printing is ready to change healthcare system architectures, enhancing persevering results and accessibility to sophisticated medical treatments as new systems and substances are combined.

**CONFLICTS OF INTEREST**

The authors declare no conflicts of interest, financial or otherwise.

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**ETHICS APPROVAL AND CONSENT TO PARTICIPATE**

Not applicable.

**CONSENT FOR PUBLICATION**

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