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IP Indian Journal of Conservative and Endodontics

Journal homepage: https://ijce.in/

Review Article

Innovative techniques in endodontics: Exploring the potential of 3D printing

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Abstract

3D printing is revolutionizing endodontics by offering enhanced precision, efficiency, and personalization in various clinical procedures. Key applications include guided endodontic access, where 3D-printed templates help clinicians navigate complex canal morphologies, reducing the risk of iatrogenic errors. This technology also aids in autotransplantation, enabling preoperative 3D-printed tooth replicas to optimize recipient site preparation, minimize extra-oral time, and preserve periodontal ligament cells, improving transplant success. Surgical guides derived from 3D printing improve the accuracy of endodontic microsurgery by precisely locating osteotomies and reducing risks to surrounding structures. Furthermore, Additionally, in regenerative endodontics, 3D printing supports the development of bioengineered scaffolds for dental pulp regeneration, fostering progress in tissue engineering. As the technology advances, its role in endodontics is expected to expand, enhancing clinical outcomes, educational practices, and the overall quality of patient care.

Keywords: 3D Printing, Endodontics, Guided endodontic access, Regenerative endodontics, Endodontic microsurgery.

Received: 20-06-025; **Accepted:** 23-08-2025; **Available Online**: 08-10-2025

1. Introduction

3D printing is an emerging technology with a wide range of applications in the dental field. It has a particular resonance with dentistry, and with advances in 3D imaging and modelling technologies such as cone beam computed tomography and intraoral scanning, and with the relatively long history of the use of Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technologies in dentistry, it will become increasingly important. The drive behind advancement in 3D printing for medicine and dentistry emerges from the possibility of individualized products, savings on small scale productions, sharing and processing of patient image data and educational upgrading 3D printing technology also called additive manufacturing; rapid prototyping uses incremental deposition of material layer by layer. It's an innovative method over the subtractive manufacturing where a block of objects is used to cut the material out.[1]

2. History

3D printing has been used increasingly since the 1980s. The idea of Additive Manufacturing (AM) was first presented by Chuck Hull in 1986 by means of a procedure known as 'stereolithography (SLA)' He made the initial 3D printer that utilized the strategy of stereolithography. They got expanded consideration in fields of engineering architecture, aeronautics and telecommunications. Later its application in general medicine started drawing attention of specialists in 1990s leading to increased research and better results in this field.[2]

2.1. 3D Printing process

The 3D printing technique involves three fundamental steps.[3]

Initially, a 3D digital model of the object is created using CAD software, often with the help of a 3D scanner. Next, the object is printed using a suitable material selected based on

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https://doi.org/10.18231/j.ijce.35922.1759917440

the intended application commonly plastics, ceramics, resins, or metals in dentistry.

Finally, the printed item undergoes a post-processing or finishing phase, which demands specialized tools and expertise to achieve the desired quality and functionality.

2.2. Modes of 3D printing

2.2.1. Stereolithography (SLA)

Stereolithography device was invented by Charles Hull in the 1980's. It has become one of the most common technologies for rapid prototyping. This was the first commercially available printer for rapid prototyping. It is a form of additive manufacturing which converts liquid material (photosensitive monomer resin) into solid parts (polymer resin) using an ultraviolet light source through photopolymerization. The reaction takes place on the surface of the material and the materials used must be photo curable like acrylics, epoxies, fabrication of titanium implants.[4]

2.2.2. Photo polymer jetting

Either a stationary print head and dynamic platform or a stationary platform and dynamic print head are used in this technique. An inkjet-style print head transfers light-sensitive polymer onto a manufacturing stage, where it is cured layer by layer on a platform that plunges gradually. A wide range of casting resins and waxes, as well as some elastic materials that resemble silicone, can be printed. With a resolution of roughly 16 microns, this technology makes it simple to create intricate and finely detailed items.[4]

2.2.3. Fused deposition modelling (FDM)

In this technique, thermoplastic material is heated until molten and then extruded through a nozzle to form the object layer by layer from the bottom up. Frequently used materials include acrylonitrile butadiene styrene (ABS), polycarbonates, and polysulfones.[5]

2.3. Selective laser sintering (SLS)

It involves the use of a laser to selectively fuse fine powder particles to create a structure layer by layer. As each layer is completed, the powder bed lowers, and a new layer of powder is evenly spread over the surface.[6] This method is widely used for producing anatomical models, surgical guides, dental models, and prototypes in engineering and design.[7]

2.4. Electron beam melting (EBM)

It employs an electron beam, instead of a laser, to fuse metal powders in a high-vacuum environment. The metal is melted layer by layer to form the final object. This technique produces dental implants with mechanical properties, corrosion resistance, and grindability comparable to those made from both precious and non-precious metal alloys.[8]

2.5. Multijet printing

It is similar to stereolithography, uses a print head to jet fine droplets of photosensitive resin in the desired pattern. A UV lamp, attached to the printer head, cures the resin layer by layer. Technologies like PolyJet and Multijet printing fall under this category, enabling high-resolution fabrication of intricate designs.[9]

2.6. ColorJet printing (CJP)

It is an additive manufacturing process that utilizes two key components: a core material and a binder. The core material is spread in thin layers over the build surface using a roller. An inkjet print head then selectively deposits the binder onto the core material, solidifying it. With each successive layer, the platform lowers slightly, allowing for the creation of full-color, three-dimensional models.[9]

2.7. 3D printing in endodontics

3D printing has carved a prolific niche in the endodontic discipline. The paradigm shifts from manual to digital workflow in endodontics has resulted in unprecedented streamlining of procedures, greater precision and accuracy, improved patient satisfaction, a breakthrough in regenerative endodontics and the development of operator skills through training and education.[10]

2.8. Applications in the field of endodontics

2.8.1. Guided endodontic access

Pulp canal obliteration presents significant challenges in endodontic treatment by making canal localization and negotiation more difficult. Factors like orthodontic treatment, aging, dental caries, and trauma can contribute to canal calcification. Notably, 15–40% of patients who experience dental trauma develop pulp canal obliteration.[11] This obliteration makes locating and negotiating root canals more difficult, increasing the complexity of treatment and the risk of procedural errors. Traditionally, clinicians rely on their anatomical knowledge and visual cues to locate canals, which becomes challenging in cases of abnormal or calcified anatomy.[12] Common complications during conventional treatment include overextended access cavities, missed canals, perforations, file separation, and deviation from the original canal trajectory.[13]

Guided endodontic access provides a more accurate and predictable alternative. By predefining the entry point, angulation, and depth of access, this technique minimizes errors common with free-hand methods. It is especially valuable for clinicians with less experience, as it supports conservative tooth structure removal. A preclinical study by Connert et al.[14] demonstrated a 92% success rate in locating severely calcified canals using guided endodontics, compared to just 42% with conventional free-hand techniques. Additionally, this approach shortened treatment time and reduced tooth structure loss, with no significant performance difference between clinicians.[15] Overall, guided endodontics enhances access, cleaning, and shaping of calcified canals, offering improved accuracy, repeatability, and usability regardless of operator experience.[15] 3D-printed guides are increasingly being used to facilitate precise access to root canals, especially in cases involving complex canal anatomy such as calcified canals. These patient-specific access templates, digitally designed to match individual teeth, promote a minimally invasive approach and reduce the likelihood of iatrogenic damage.[16]

2.8.2. Autotransplantation

Achieving success in tooth autotransplantation depends heavily on maintaining the viability of periodontal ligament (PDL) cells and ensuring the transplanted tooth fits properly within the recipient socket. Conventional techniques often involve multiple trial insertions of the donor tooth, increasing the risk of PDL trauma and prolonged extra-oral time.[17] Early studies by Lee & Kim demonstrated that using computer-aided rapid prototyping (CARP) to create tooth replicas allows clinicians to prepare the recipient site before actual extraction, thus protecting PDL cells and improving transplant success.[18,19] In a case report, Strbac et al.[20] demonstrated the successful autotransplantation of immature premolars to replace an avulsed maxillary incisor using a fully digital workflow. Computer-aided design (CAD) was utilized to select suitable donor teeth based on their dimensions and stage of root development. Prototype models were digitally modified to accommodate the anatomical space of Hertwig's epithelial root sheath and to minimize trauma to the apical papilla. These CAD-designed prototypes were virtually positioned into the recipient sites to design a series of progressively larger osteotomy guides, enabling a more accurate and efficient surgical procedure. In a proof-of-concept study, Anssari Moin et al.[21] employed CAD to create custom surgical tools tailored to the donor tooth. This technique achieved high precision, with apical deviation of less than 1 mm from the planned tooth position in a human mandible model. Supporting this approach, a systematic review by Verweij et al.[22] reported an overall success rate of 80–91% for autotransplantation when rapid prototyping techniques were used. The success was attributed to accurate preparation of the recipient site prior to tooth extraction, which in some cases reduced the extraoral time to under one minute.

2.8.3. Educational models and clinical simulation

The incorporation of 3D printing technology into preclinical endodontic education has introduced a significant shift from traditional teaching methods. It enables students to visualize dental anatomies in three dimensions while also offering physical models of root canal configurations. These models allow learners to practice and refine their endodontic skills with greater precision and efficiency.[23]

Advances in CAD/CAM materials enable more realistic substitutes to extracted teeth. Kfir et al. used a transparent tooth replica to replicate perfect access, instrumentation, and obturation in a difficult type 3 dens invaginatus scenario prior to treating the clinical case.[24]

Pouhaër et al. investigated the application of transparent liquid resin in creating large-scale macromodels for undergraduate training. These models proved valuable in enhancing the visualization of root canal anatomy and facilitating access cavity preparation.[25] Reymus et al. explored the use of SLA technology for fabricating artificial teeth for endodontic training. Their findings demonstrated that 3D-printed photopolymer teeth made from photosensitive resin closely replicate natural teeth and hold significant potential for use in preclinical education.[26]

3D printing has been utilized in pre-clinical research to produce multiple identical prototypes, enabling consistent and controlled experimentation. This has allowed for the evaluation of various parameters, including the shaping performance of different rotary file systems, stress distribution, centering accuracy of access cavity preparations, and the effectiveness of various obturation techniques in C-shaped canals, all using standardized canal configurations.[27-30]

2.9. 3D Model Reconstruction

Dental structures can be captured as 3D images and processed using software to create customized models. These digitally reconstructed models can be edited and printed within hours, providing tangible replicas that enhance visualization and understanding of the targeted anatomical region.[31]

2.9.1. Guided post removal

Fiber-reinforced composite posts are commonly used to retain core material and reinforce the root in endodontically treated teeth. However, when root canal retreatment is needed, post removal becomes necessary and can be quite challenging. Traditional tools such as dedicated post removal kits, ultrasonic instruments, long-shank burs, and operating microscopes are used, but they still carry risks including canal deviation, root weakening, and perforation.[32]

The use of 3D-printed surgical guides has emerged as a valuable solution, enabling precise control of the drill's angulation during post removal. These guides help maintain the correct axis, reducing the likelihood of procedural errors. In a case report, Pérez et al.[33] successfully demonstrated the use of a 3D-printed surgical guide to remove a fiberglass post from the palatal canal of a maxillary first molar, illustrating the clinical feasibility and precision of this technique.

2.9.2. Surgical guides in endodontic microsurgery

Another important application of 3D printing in endodontics is the fabrication of patient-specific appliances and surgical guides, advancing the scope of personalized treatment.[34] The use of 3D-printed instruments enhances surgical precision, improves treatment outcomes, and reduces the risk of failure. In addition, 3D printing has proven highly valuable in endodontic education, as it allows the reproduction of complex root canal anatomies. These printed models provide trainees with improved visualization and hands-on practice opportunities, thereby ensuring better preparation for clinical procedures.[35]

Clinicians continue to experience difficulties in posterior molar scenarios or in cases where anatomical structures approach the root end, possibly leading to the extraction of otherwise serviceable teeth.3D printed stents can reduce risk by avoiding encroachment on neurovascular structures and adjacent teeth, and by targeting osteotomy perforation sites.[36] The use of 3D printing in endodontic microsurgery has shown promising results, with CBCT-based surgical guides enabling more precise localization of osteotomy sites compared to conventional freehand techniques in in vitro studies.[37] Patel et al. demonstrated the use of a 3D printed custom tissue retractor to enhance visualization and soft tissue handling during endodontic microsurgery on a maxillary incisor.[38]

2.9.3. Guided endodontics in periapical surgery

Endodontic surgery, or apicoectomy, is typically indicated for the management of apical periodontitis in cases that fail to resolve following nonsurgical retreatment or, in some instances, after primary root canal therapy particularly when complications such as overfilled canals, fractured instruments, intracanal posts, or crown restorations are present alongside persistent apical pathology. Advances in modern surgical techniques have improved treatment outcomes and include the use of magnification tools such as loupes or dental microscopes, as well as minimally invasive ultrasonic instruments.[39] The procedure involves accessing the affected area through soft tissues and cortical bone, followed by the resection of approximately 3 mm of the root apex.[40,41] Traditionally, apicoectomies are performed freehand, relying on two-dimensional radiographs for guidance and the clinician's skill in visual perception and hand-eye coordination to locate and resect the root apex accurately.[42] The presence of anatomical structures such as the inferior alveolar nerve, greater palatine artery, mental foramen, or maxillary sinus in close proximity to the surgical site can significantly complicate the procedure and increase the risk of complications, occasionally rendering surgery inadvisable. Furthermore, a thick cortical plate can obscure the root apex, making it more difficult to locate and often leading to unnecessary removal of healthy bone.[43] Maintaining surgical precision while preserving surrounding healthy tissues and achieving adequate visualization remains a considerable challenge for endodontists.[44] Trephine burs, when combined with a 3D-printed surgical guide, can facilitate osteotomy, root-end resection, and biopsy in a single step and this technique is referred to as targeted endodontic microsurgery (TEMS).[45,46] This approach provides a precise pathway to the root end requiring resection, with the osteotomy size, apical resection level, and bevel angle predetermined before surgery. As a result, unnecessary removal of healthy alveolar bone is minimized, and adjacent soft tissues, neurovascular structures, and mucosa are preserved, thereby reducing postoperative trauma and swelling.

In an in vitro study, Peng et al. demonstrated that TEMS significantly reduced both length and angle deviations in root-end resection compared to freehand techniques ($P < 0.05$), enabling even less-experienced clinicians to achieve outcomes comparable to those of skilled practitioners.[47] Similarly, Kim et al. reported that TEMS is less technique-sensitive than conventional methods.[48] Beyond accuracy, TEMS also improves efficiency by shortening surgical and patient chair time. In an ex vivo study, three board-certified endodontists treated six maxillary and six mandibular teeth using both guided and freehand approaches. The guided technique reduced mean surgical time from 14 minutes to just 4 minutes, while also significantly lowering bevel angle deviations and minimizing unnecessary over-resection. Clinical evidence further supports these findings. In one study, endodontic faculty and residents performed TEMS on 24 teeth, achieving a 91.7% success rate, with only a single case showing radiographic evidence of failure. The authors concluded that targeted microsurgery provides outcomes comparable to traditional microsurgery, with added benefits of precision and efficiency.[49]

2.9.4. Dental pulp regeneration

3D printer can print bone tissue tailored to requirement of patients act as biomimetic scaffold. These days there are 3d printed alginate peptide hybrid scaffolds, which act as a stable medium for the optimal growth of stem cells. Calcium 3D cell printing technique can be utilized for replacing pulp tissue. Pulp tissue architecture can be replicated using an inkjet bioprinting approach, where layers of hydrogel-embedded cells are carefully deposited. This technique allows for the precise arrangement of cells, closely imitating the natural structure of dental pulp. Specifically, odontoblastic cells are positioned around the outer layer, while fibroblasts occupy the central region, supported by a network of vascular and neural cells. Ongoing research aims to develop fully functional pulp-like tissue through this method.[50,51]

2.9.5. Repair of bony/soft tissue defects

Defects resulting from trauma, surgical procedures, or congenital conditions can be addressed using 3D-printed scaffolds designed in various geometries through personalized tissue engineering approaches. Techniques like rapid prototyping and solid freeform fabrication play a crucial role in creating these tailored scaffolds. Materials such as polyethylene oxide and polyethylene glycol dimethacrylate photopolymerizable hydrogels have been used to produce constructs that closely resemble soft tissues in elasticity, support high cell viability, and achieve dense cellular structures.[52]

2.9.6. Advantages of 3D printing

1. Time-Efficient: 3D printing significantly reduces the time required for fabrication compared to traditional methods.
2. High Accuracy and Reproducibility: Precise scanning and digital workflows ensure detailed, high-quality output with consistent results.[53]

2.9.7. Disadvantages of 3D printing

1. High Initial Investment: The setup cost for 3D printing technology remains a significant barrier, particularly for smaller dental practices or institutions.
2. Limitations in Final Part Quality: One of the most critical drawbacks of 3D printing is the compromised structural integrity of the final product. Since components are built layer by layer, this process can introduce inherent weaknesses at the interfaces between layers.[53]
3. Need for Post-Processing: The final strength of 3D-printed materials often depends on additional post-processing steps. For instance, materials like zirconia and E-max, commonly used in restorative dentistry, require sintering after milling to achieve optimal mechanical properties.[53]

3. Discussion

The adoption of 3D printing in endodontics reflects a broader digital transformation in dentistry, where imaging, planning, and manufacturing converge to deliver personalized, minimally invasive treatment. Across its applications guided endodontic access, auto transplantation, microsurgical procedures, regenerative scaffolds, and education, common advantages emerge improved accuracy, reduced chairside time, and enhanced predictability compared to conventional freehand methods.

3.1. Future prospective

3D bioprinting marks a significant breakthrough in additive manufacturing by enabling the construction of complex, three-dimensional structures that integrate living cells, biomaterials, and bioactive molecules. The process relies on bioinks—mixtures of cells, growth factors, and hydrogels—that are deposited in controlled layers to form intricate tissue frameworks.[54] The process involves several critical stages, beginning with the preparation of bioinks designed to mimic the extracellular matrix (ECM), followed by the selection of an appropriate printing method, such as inkjet-based,[55,56] extrusion-based,[57] or laser-assisted techniques,[58] to support tissue maturation and functionality.

Among these, inkjet bioprinting adapts conventional inkjet principles, using thermal, piezoelectric, or electrostatic forces to dispense bioinks layer by layer. This technique offers high resolution, cost-effectiveness, and good cell viability, but is restricted to low-viscosity bioinks to avoid nozzle clogging, and scalability for larger constructs remains a challenge. Nonetheless, it has been effectively applied in fabricating skin, cartilage, and vascular tissues, as well as tissue models for pharmaceutical research.[59-62] Extrusion-based bioprinting (EBB), on the other hand, employs pneumatic or mechanical pressure to extrude continuous streams of bioink. It is particularly suited for producing large, mechanically stable scaffolds and can accommodate a wide range of bioink viscosities, making it valuable in the creation of bone,[63] cartilage, and organ constructs.[64] However, it generally offers lower resolution compared to inkjet and laser-assisted systems, and excessive pressure during printing may compromise cell viability.

In dentistry, 3D bioprinting holds tremendous promise as it enables the fabrication of patient-specific restorations, such as crowns, bridges, and dentures that provide superior fit and comfort. Moreover, its role in dental tissue engineering is rapidly expanding, particularly in periodontal regeneration and alveolar bone reconstruction. By producing hybrid and biphasic scaffolds in combination with stem cells and biomaterials, this technology offers highly personalized, biocompatible, and functionally complex treatment options.[65] Beyond regenerative applications, 3D bioprinting also facilitates the precise fabrication of dental models, surgical guides, and restorations using ceramics and composites, thereby improving treatment accuracy and patient comfort while driving innovation within clinical dentistry. Ultimately, the success of regenerative dentistry depends on selecting the most appropriate bioprinting technique and material type to reliably construct functional dental tissues.[66]

4. Conclusion

Three-dimensional (3D) imaging and modeling are profoundly transforming modern endodontic practice by offering unprecedented levels of accuracy, efficiency, and customization. These technologies serve not only as diagnostic aids but also as powerful tools for preoperative planning, procedural guidance, and simulation. Among the most promising innovations is 3D printing, which enables the fabrication of precise, patient-specific models, surgical templates, and endodontic training aids with minimal time and material wastage. The integration of 3D printing into endodontics holds immense potential to become a milestone in the field. Its accuracy in replicating complex root canal anatomies and periapical pathologies allows clinicians to plan and perform procedures with greater confidence and reduced risk of iatrogenic errors. Applications such as guided endodontic access, post removal, surgical resection, autotransplantation, and regenerative therapies benefit greatly from the precision that 3D-printed tools and guides provide. Additionally, its rapid prototyping capabilities streamline the workflow, reducing chairside time and improving overall patient outcomes. Furthermore, 3D visualization enhances patient communication and understanding by allowing them to see simulated treatment outcomes, which can aid in informed consent and compliance. In academic and training environments, 3D printed tooth models allow students and practitioners to practice on realistic anatomical replicas, thereby improving clinical skills and decision-making. In summary, 3D printing presents a promising future for both surgical and non-surgical endodontics. As technological advancements continue to refine its capabilities, it is expected to play an increasingly vital role in delivering precise, minimally invasive, and patient-centered endodontic care.

5. Source of Funding

None.

6. Conflict of Interest

None.

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Cite this article: Deepika, Rashid S, Gupta VA, Nagpal AK, Choudhary S. Innovative techniques in endodontics: Exploring the potential of 3D printing. *IP Indian J Conserv Endod*. 2025;10(3):155-161.