International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 122-131 www.ijdmsrjournal.com ISSN: 2582-6018

"Advancements in 4D Printing Technology and Its Emerging Applications in Prosthodontics"

Dr. Nitin Sethi[1], Dr. Monika Negi[2], Dr. Parikshit Gupt[3], Dr. Anuj Sharma[4], Dr. Ishika Kaushik[5], Dr. Ankita Dadwal[6]

1. *Professor and Head, Department of Prosthodontics, Crown & Bridge and Implantology, Himachal Institute of DentalSciences, Paonta Sahib, Himachal Pradesh*
2. *Post - Graduate Student, Department of Prosthodontics, Crown & Bridge and Implantology, Himachal Institute of DentalSciences, Paonta Sahib, Himachal Pradesh*
3. *Reader, Department of Prosthodontics, Crown & Bridge and Implantology, Himachal Institute of DentalSciences, Paonta Sahib, Himachal Pradesh*
4. *Professor, Department of Prosthodontics, Crown & Bridge and Implantology, Himachal Institute of DentalSciences, Paonta Sahib, Himachal Pradesh*
5. *Post - Graduate Student, Department of Prosthodontics, Crown & Bridge and Implantology, Himachal Institute of DentalSciences, Paonta Sahib, Himachal Pradesh*
6. *Post - Graduate Student, Department of Prosthodontics, Crown & Bridge and Implantology, Himachal Institute of DentalSciences, Paonta Sahib, Himachal Pradesh*

Date of Submission: 10-09-2025 Date of Acceptance: 20-09-2025

I. INTRODUCTION

4D printing is an innovative extension of 3D printing that adds the dimension of time to the creation of objects, resulting in the ability for printed materials to change shape, functionality, or properties over time in response to external stimuli such as temperature, light, moisture, or pH (Tibbets et al., 2016). Unlike 3D printing, which produces fixed, unchanging structures, 4D printing enables objects to modify their form or behavior over time in response to specific environmental triggers such as heat, moisture, light, or pH levels (Tibbets et al., 2016). This is achieved using advanced materials known as stimuli-responsive or smart materials, which are engineered to respond predictably to changes in their surroundings (Chen et al., 2020; Momeni et al., 2020).

The underlying concept of 4D printing involves integrating responsive materials that allow printed components to change shape or function after fabrication. Materials commonly used include programmable polymers, hydrogels, and composites that exhibit changes such as expansion, contraction, or shape restoration based on external cues (Wu et al., 2018). This evolution in additive manufacturing makes it possible to create systems that go beyond static applications, offering adaptable, reconfigurable, and potentially self-healing solutions (Pikul et al., 2017).

Fundamentally, the distinction between 3D and 4D printing lies in the material response and design purpose. While 3D printing focuses on fabricating stable, non-adaptive structures, 4D printing is centered on creating constructs capable of transformation. These transformations are driven by tailored materials that react to stimuli such as thermal changes, water absorption, or light exposure (Zhao et al., 2017). This added functionality enables new possibilities in industries like soft robotics, biomedical devices, and dentistry, where adaptation to environmental changes can significantly enhance performance (Wang et al., 2019).

Material science is critical in advancing 4D printing technology. Stimuli-responsive materials such as shape-memory polymers (SMPs) and hydrogels play a central role in enabling temporal transformations. SMPs can be deformed and later recover their original shape upon exposure to heat or light (Yuan et al., 2020). Similarly, hydrogels respond to stimuli like pH or temperature by altering their volume, making them suitable for applications requiring flexibility and responsiveness (Zhu et al., 2017). Developing and fine-tuning these materials is essential for improving the functionality, reliability, and precision of 4D-printed products (Momeni et al., 2020).

In the medical field, 4D printing is gaining attention for its ability to produce personalized and adaptive solutions. Particularly in prosthetics and orthotics, this technology allows the design of devices that conform to a patient’s changing anatomy over time, enhancing fit and comfort (Zhang et al., 2021). In prosthodontics, 4D-printed dental components could potentially adjust to the oral environment, improving integration and reducing failure risks (Gao et al., 2020). The inclusion of self-healing features could also increase the durability of dental materials (Bourgeois et al., 2020).

However, several challenges must be addressed for broader clinical use. These include developing safe, long-term biomaterials (Kang et al., 2019), navigating regulatory pathways, and overcoming the financial and technical demands associated with the technology (Alagoz et al., 2021).

II. LITERATURE REVIEW

The evolution of printing technologies has significantly impacted healthcare, especially dentistry. The introduction of 3D printing in the 1980s—initiated by Chuck Hull's development of stereolithography (Hull, 1986)—enabled fabrication of three-dimensional objects directly from digital models. This advancement eventually found widespread application in fields like automotive and aerospace and later transitioned into dentistry during the early 2000s. Initially, it was used to produce diagnostic models, crowns, and bridges (Pilloni et al., 2015). With ongoing improvements in material science and digital imaging, 3D printing expanded to the creation of customized dental implants and surgical guides (Liu et al., 2020).

More recently, 4D printing emerged as an evolution of 3D printing, adding time as a functional dimension. This innovation enables printed structures to change their form or properties in response to environmental factors like heat, moisture, light, or pH (Tibbets et al., 2016). This adaptability is particularly beneficial in dentistry, where materials that can adjust in situ offer new possibilities for responsive and patient-specific devices (Liu et al., 2020).

At the heart of 4D printing lies the use of smart, stimuli-responsive materials. Unlike static objects created by 3D printing, 4D-printed constructs can undergo controlled transformations over time when exposed to specific stimuli (Wu et al., 2018). Such behavior is achieved through materials like shape-memory polymers (SMPs), which revert to a predetermined form when activated by heat or light (Yuan et al., 2020), and hydrogels, which react to changes in moisture or pH, offering potential for self-adjusting or healing mechanisms in biomedical applications (Zhu et al., 2017).

In prosthodontics, the shift from 3D to 4D printing introduces new capabilities. While 3D printing offers precision and patient-specific customization, it produces fixed structures. Conversely, 4D printing enables the production of devices that can adapt post-fabrication. For example, implants could adjust their fit over time to accommodate bone resorption or thermal fluctuations in the oral cavity (Zhao et al., 2017; Zhang et al., 2021). This dynamic functionality supports greater long-term integration and patient comfort.

Despite these benefits, practical limitations remain. One significant barrier is the development of materials that are not only responsive but also biocompatible and stable within the oral environment over time (Kang et al., 2019). Additionally, the high cost of 4D printing technologies and the requirement for specialized machinery present logistical hurdles to implementation in everyday clinical practice (Alagoz et al., 2021). Regulatory challenges also exist, as such innovative devices must pass rigorous evaluation before being approved for human use (Momeni et al., 2020).

III. TECHNOLOGICAL ADVANCES IN 4D PRINTING

4D printing has advanced significantly through innovations in materials and fabrication techniques, particularly in applications like prosthodontics, where adaptability and durability are essential.

A major area of progress involves smart materials capable of reacting to environmental stimuli. These include self-healing materials, which are engineered to repair minor damage through embedded agents released upon structural disruption. This feature is highly beneficial in dental prosthetics, where microfractures can reduce function and longevity (Yuan et al., 2020; Zhao et al., 2017). Another essential innovation is shape-memory polymers (SMPs), which revert to a predetermined shape when activated by heat, light, or moisture. In dentistry, SMPs allow devices such as orthodontic appliances or implants to adjust post-placement, responding to intraoral changes and enhancing fit and patient comfort (Wu et al., 2018). Similarly, hydrogels, which swell or contract with pH or temperature shifts, provide potential for adaptive dental devices that respond to physiological changes (Zhu et al., 2017).

Progress in printing techniques has further supported the use of such advanced materials. Stereolithography (SLA), known for high resolution, is particularly suited for dental applications requiring precise, patient-specific designs (Tibbets et al., 2016). Fused Deposition Modeling (FDM) enables layer-by-layer construction using thermoplastic filaments, making it compatible with SMPs and hydrogels for experimental dental models (Yuan et al., 2020). Inkjet printing, another promising technique, allows for selective placement of responsive materials, enabling the fabrication of customized, functional prosthetics with localized stimulus response (Momeni et al., 2020).

Recent developments show practical use cases in prosthodontics. Self-adjusting implants, capable of modifying shape in response to oral conditions like temperature or bone remodeling, offer improved integration with surrounding tissues (Zhang et al., 2021). 4D-printed dentures, made from adaptive polymers, may adjust automatically to gum and bone changes, reducing the need for repeated fittings (Gao et al., 2020). In orthodontics, devices made with 4D techniques can gradually shift in shape to apply controlled forces, reducing the frequency of manual adjustments while improving treatment outcomes (Wu et al., 2018).

IV. EMERGING APPLICATIONS OF 4D PRINTING IN PROSTHODONTICS

Recent advancements in 4D printing are paving new paths in prosthodontics by enabling the creation of adaptive, patient-specific dental devices. Unlike conventional prosthetics, which often require multiple adjustments and manual interventions, 4D-printed solutions offer dynamic functionality tailored to the oral environment. These developments are redefining how dental prostheses are designed, customized, and integrated.

Personalized Prosthetic Devices

One of the standout benefits of 4D printing in dental applications is the ability to fabricate prosthetics that adjust to the patient's oral changes over time. Traditional methods often struggle to accommodate anatomical variations that occur due to gum recession, bone remodeling, or tissue shifts. Using shape-memory materials and other stimuli-responsive compounds, 4D printing allows for implants and dentures that conform to evolving contours of the oral cavity (Gao et al., 2020).

These smart materials can be programmed to respond to specific external triggers—such as temperature or pressure—which enables them to reshape or modify their mechanical properties after placement. For instance, dental crowns or bridges might adjust slightly when exposed to heat from food, ensuring a better fit and reducing long-term complications like loosening or discomfort (Zhang et al., 2021). As a result, 4D-printed prostheses provide superior patient comfort while minimizing follow-up appointments or corrective procedures (Zhao et al., 2017).

Advancements in Oral Tissue Engineering

Beyond prosthetic devices, 4D printing has shown considerable promise in the realm of regenerative dentistry. It facilitates the production of intelligent scaffolds that not only support tissue regeneration but also interact dynamically with their biological environment. These scaffolds can adjust their shape, porosity, or stiffness in response to physiological changes, making them ideal for promoting bone and soft tissue growth following surgeries or tooth loss (Li et al., 2020).

Hydrogels and similar biocompatible materials are often used for these scaffolds due to their ability to respond to changes in pH, temperature, or cellular activity. Once implanted, these materials adapt to the wound site, supporting healing and facilitating cell proliferation without rigid constraints (Liu et al., 2020). Over time, they can dissolve or morph in ways that encourage integration with natural tissue, potentially reducing reliance on synthetic grafts or repetitive surgeries (Momeni et al., 2020). Their use in guided tissue regeneration offers transformative potential for dental implants, particularly in patients with compromised oral structures.

Smart Prostheses and Responsive Devices

A major innovation driven by 4D printing is the concept of "smart" dental prostheses—devices that sense and react to their environment to maintain comfort, fit, and functionality. These devices can undergo changes in shape, elasticity, or volume depending on stimuli such as intraoral temperature, moisture levels, or mechanical forces (Zhao et al., 2017). In practical terms, this means dentures that adjust during daily wear, aligners that subtly adapt to shifting teeth, or splints that regulate pressure without manual intervention.

For orthodontic care, such adaptive technologies offer significant advantages. Instead of relying on frequent adjustments, appliances fabricated with 4D printing can self-regulate pressure and positioning over time, leading to more efficient treatments and fewer in-person consultations (Wu et al., 2018). These devices could also improve patient compliance and comfort by maintaining consistent therapeutic pressure without excessive tightening or discomfort.

The use of shape-memory alloys and polymers in prostheses represents another leap forward. For example, dentures constructed with these materials can adapt to variations in oral temperature—expanding or contracting as needed to ensure a secure and comfortable fit (Pikul et al., 2017). This responsiveness not only improves wearability but also reduces the occurrence of friction-related sores, slippage, or instability during speaking or eating.

Integration and Future Implications

The potential applications of 4D printing in prosthodontics extend well beyond mechanical responsiveness. Its integration with digital imaging and computer-aided design (CAD) systems allows for precise fabrication based on patient-specific data. By merging digital impressions with smart materials, clinicians can produce highly accurate devices that evolve in response to environmental and biological cues.

Furthermore, these innovations align with broader trends in personalized medicine. As dental treatments increasingly shift toward customization and minimally invasive solutions, 4D printing offers tools that meet both functional and aesthetic demands. Whether creating adaptive dentures for aging patients or regenerative scaffolds for post-extraction healing, this technology bridges the gap between engineering and biology.

However, widespread clinical adoption still faces challenges. The development of reliable, cost-effective, and fully biocompatible materials remains a key focus. Long-term performance data and regulatory approvals will also play crucial roles in ensuring safety and efficacy across diverse patient populations.

V. CLINICAL IMPLICATIONS OF 4D PRINTING IN PROSTHODONTICS

The introduction of 4D printing into prosthodontics brings promising clinical benefits, particularly in improving patient comfort, treatment efficiency, and cost-effectiveness.One of the primary clinical advantages is the development of **adaptive prosthetics**. Unlike conventional dental devices that often require multiple visits for refitting, 4D-printed prostheses respond to changes within the oral cavity. Materials such as shape-memory polymers allow dental implants, dentures, and aligners to reshape in response to temperature or pressure variations, maintaining a consistent and comfortable fit as oral tissues evolve (Zhang et al., 2021). This responsiveness minimizes the need for repeated adjustments and enhances long-term prosthetic function (Zhao et al., 2017).

Another significant benefit is the **functional longevity** of these devices. As 4D-printed materials can accommodate changes like gum shrinkage or bone resorption, they reduce the risk of improper fit or failure. Additionally, some smart materials offer self-healing capabilities, allowing minor damage to be repaired without clinical intervention, which contributes to improved durability and overall patient satisfaction (Gao et al., 2020).

From an operational standpoint, 4D printing also enhances **efficiency and reduces costs**. Conventional fabrication methods involve labor-intensive steps and customized fittings, while 4D printing streamlines this process by enabling direct digital-to-device production. This leads to shorter turnaround times and faster delivery of personalized prosthetics (Tibbets et al., 2016). Over time, the reduced need for adjustments and remakes also contributes to cost savings for both clinics and patients (Wu et al., 2018).

Despite these advantages, several **barriers hinder clinical adoption**. Regulatory approval remains a major hurdle, as all new dental materials must undergo thorough safety and performance evaluations before clinical use (Momeni et al., 2020; Gao et al., 2020). Additionally, **patient awareness and acceptance** may be limited. Educating patients on the safety and reliability of these dynamic devices is essential to build trust (Zhang et al., 2021).

Finally, successful integration into dental practice requires **specialized training**. Dental professionals must become proficient with new design tools, materials, and 4D printing equipment. Without adequate education and upskilling, the transition to this advanced technology may face resistance (Alagoz et al., 2021).

VI. FUTURE DIRECTIONS AND POTENTIAL OF 4D PRINTING IN PROSTHODONTICS

The future of 4D printing in prosthodontics is marked by promising advancements in material science, intelligent design, and clinical integration. Emerging innovations are expected to make dental prosthetics more adaptive, personalized, and effective.

Upcoming developments in smart materials will significantly expand the capabilities of 4D-printed dental devices. Enhanced shape-memory polymers (SMPs) are anticipated to offer quicker responses and more precise shape transformations triggered by a variety of stimuli such as temperature, humidity, or even electrical fields (Zhao et al., 2017). These improvements will enable the fabrication of prostheses that adjust more dynamically to changes in the oral cavity, maintaining comfort and fit over time.

In parallel, biocompatibility will remain a focal point. Future materials will be engineered to better match the physical and mechanical properties of bone and soft tissue, promoting improved healing and integration. Such advances will enhance outcomes in regenerative procedures by supporting natural tissue growth around implants and scaffolds (Gao et al., 2020).

A transformative shift is also expected through the integration of artificial intelligence (AI) and machine learning. By analyzing detailed patient data, AI can support the design of prostheses tailored to individual anatomy and clinical needs. These technologies can also forecast how materials behave long-term, optimizing durability and functionality (Wu et al., 2018). Incorporating AI into design software may automate and streamline the customization process, reducing production time and costs (Zhang et al., 2021).

The long-term impact on dental practice will be substantial. As 4D printing becomes more accessible, traditional prosthetic methods may give way to adaptive devices that reduce the need for manual adjustments and replacements. These devices could be designed to self-adjust, self-repair, or promote regeneration, reducing complications and enhancing patient outcomes (Li et al., 2020).

In the broader context of dental care, 4D printing supports a shift toward preventive and regenerative prosthodontics. Devices that respond to biological cues—like pH or tissue changes—could enhance healing and improve implant stability (Momeni et al., 2020).

Over time, this technology may lead to lower healthcare costs through reduced need for repeated procedures. Combined with AI-driven automation, 4D printing has the potential to make advanced prosthodontic care faster, more reliable, and widely available (Tibbets et al., 2016).

VII. CONCLUSION

The advent of 4D printing introduces a significant leap in prosthodontics by enabling the fabrication of dental prostheses that adapt over time to changes in the oral environment. Unlike traditional prosthetic materials, those used in 4D printing—such as shape-memory polymers and hydrogels—respond to external stimuli like temperature or moisture. This responsiveness enhances fit, function, and patient comfort, reducing the need for frequent manual adjustments.

Beyond comfort and adaptability, this technology shows great promise in regenerative dentistry. Smart scaffolds created using 4D printing can facilitate tissue regeneration and better integration with surrounding bone or soft tissues. Furthermore, smart prosthetics that react to environmental changes can offer real-time benefits, adjusting functionality based on a patient's needs. As artificial intelligence and machine learning become increasingly intertwined with 4D printing, the customization and efficiency of prosthetic manufacturing are likely to improve dramatically.

However, several barriers must be addressed before mainstream adoption is feasible. These include challenges in creating safe, long-lasting, and biocompatible materials, as well as navigating the regulatory processes for clinical approval. High costs, limited access to training, and acceptance among practitioners also hinder wider implementation.

In summary, 4D printing has the potential to redefine prosthodontic care by delivering prosthetics that are more adaptive, durable, and personalized. Continued interdisciplinary collaboration and robust clinical research will be essential to overcome current limitations and fully integrate this technology into everyday dental practice.

REFERENCES

[1]. Aghakhani M, Hasani-Sadrabadi M, Gaharwar AK. (2024). Programmable hydrogels for 4D printing of oral tissue scaffolds. Advanced Healthcare Materials, 13(3), e2300275.
[2]. Ahmadi R, Rafsanjani A, Javid F. (2023). Shape-memory polymers in maxillofacial prosthetics: A systematic review. Journal of Prosthetic Dentistry, 129(2), 212-223.
[3]. Alagoz C, Khan M, Kumar P. (2021). Future directions of 4D printing in healthcare and prosthetics. Medical Devices and Therapeutics, 15(2), 104-116.
[4]. Ali N, Siddiqui DA, Afzal A. (2020). Smart materials in dentistry: From passive to active prostheses. International Journal of Prosthodontics, 33(5), 489-499.
[5]. Alifui-Segbaya F, Lannigan R, Ahmed I. (2019). Additive manufacturing for removable partial dentures: Current status. British Dental Journal, 226(11), 803-810.
[6]. Al-Khayatt A, Zhang M, Wang Y. (2022). Self-healing dental composites: Concepts and clinical prospects. Dental Materials, 38(6), 860-872.
[7]. Anusavice KJ, Shen C, Rawls HR. (2021). Phillips' Science of Dental Materials (13th ed.). Elsevier.
[8]. Armbrecht B, Mantini F, Marzi R. (2023). AI-driven optimization of 4D printed splints. Computers in Biology and Medicine, 161, 106109.

[9]. Ashammakhi N, Nasiri R, Barros N. (2020). 4D bioprinting: Hype or hope? Materials Today, 34, 146-166.
[10]. Bagheri R, Akash MS, Khosla A. (2024). Multi-stimuli hydrogels for adaptive temporomandibular joint discs. Journal of Biomedical Materials Research B, 112(1), 34-47.
[11]. Bansal R, Patel P, O'Connor LJ. (2022). Digital workflow for 4D printed post-and-core systems. Clinical Oral Investigations, 26(9), 5545-5557.
[12]. Basu S, Bhattacharya S. (2018). Stimuli-responsive dental resins: State of the art. Journal of Adhesive Dentistry, 20(4), 287-296.
[13]. Behl M, Kratz K, Zotzmann J. (2021). Shape-memory polymers in medicine. MRS Bulletin, 46(1), 24-30.
[14]. Ben-Nissan B, Choi AH. (2021). Advances in Calcium Phosphate Biomaterials (2nd ed.). Springer.
[15]. Bencharit S, Kois JC, Olsen E. (2022). Digital dentistry and AI: Impact on fixed prosthodontics. Journal of Prosthodontics, 31(7), 561-569.
[16]. Bourgeois D, Alim A, Glover E. (2020). Advancements in the application of 4D printing in prosthodontics. International Journal of Prosthodontics, 33(3), 456-466.
[17]. Bowman SM, King KC, Schuster SJ. (2023). 4D printed orthodontic aligners: A pilot in-vitro study. American Journal of Orthodontics and Dentofacial Orthopedics, 164(4), 482-491.
[18]. Cai M, Lee J, Chen X. (2024). Machine learning-guided design of bioactive scaffolds for craniofacial bone regeneration. Bio-Design and Manufacturing, 7(1), 124-137.
[19]. Calvino M, Goyanes A, Basit AW. (2019). 4D printing in pharmaceuticals and biomedicine. Trends in Biotechnology, 37(12), 1179-1190.
[20]. Campbell TA, Ivanova OA, Kuwelkar K. (2020). Smart dental prostheses with integrated sensors. Sensors, 20(14), 3929-3942.
[21]. Capshaw CR, Pravica SA, Zafar S. (2019). Emerging applications of additive manufacturing in periodontology. Periodontology 2000, 81(1), 190-205.
[22]. Chen L, Huang Y, Wu J. (2020). Advances in 4D printing technology and its biomedical applications. Journal of Materials Science, 55(5), 1630-1643.
[23]. Chen Y, Lv C, Yang D. (2023). Photo-responsive hydrogels for dental pulp regeneration. Bioactive Materials, 18, 113-126.
[24]. Chia HN, Wu BM. (2015). Recent advances in 3D printing of biomaterials. Journal of Biological Engineering, 9, 4.
[25]. Choi JH, Ahn S, Jeong S. (2024). Nanocomposite shape-memory resins for additively manufactured crowns. Dental Materials, 40(1), 1-11.
[26]. Chu T-M, Wazir AK, Kuhn LT. (2021). Bioceramics in dentistry: Past, present, and future. Dental Clinics of North America, 65(3), 499-532.
[27]. Coste-Manière E, Gourrier A, Pouzet M. (2023). Digital workflows in implant dentistry: AI meets 4D printing. Clinical Oral Implants Research, 34(2), 108-121.
[28]. Damanik FF, Warmadewanthi D, Abdurohman H. (2022). Mechanical behavior of 4D printed SMP dental clasps. Materials Science & Engineering C, 137, 111228.
[29]. Darvell BW. (2018). Materials Science for Dentistry (10th ed.). Woodhead Publishing.
[30]. Dash R, Kundu D, Das S. (2021). Self-healable polymer networks for dental composites. Polymer Reviews, 61(3), 513-542.
[31]. Dehurtevent M, Hadida H, Rignon-Bret C. (2017). Clinical communication: Impact of 3D printing in removable prosthodontics. Journal of Prosthetic Dentistry, 118(4), 574-579.
[32]. Deng Y, Chin HC, Lu X. (2024). Multi-material DLP 4D bioprinting for oral mucosa models. Biofabrication, 16(2), 024101.
[33]. Dhawan A, Chopra S, Modi R. (2022). Applications of AI in removable prosthodontics: A review. Journal of Indian Prosthodontic Society, 22(1), 5-12.
[34]. Dilberoglu UM, Gharehpapagh B, Yaman U. (2020). Current trends in 4D printing for medical devices. Rapid Prototyping Journal, 26(1), 151-167.
[35]. Doraiswamy V, Narayan RJ. (2020). Hydrogel-based 4D-printed constructs for oral tissue engineering. Journal of Biomedical Materials Research A, 108(8), 1767-1781.
[36]. Du P, Tang J, Chen C. (2019). Advances in shape-memory alloys for biomedical

applications. Advanced Engineering Materials, 21(9), 1900204.
[37]. Elsayed H, Kuehni B, Bozec L. (2021). In-situ monitoring of SLA-printed denture bases. Polymers, 13(6), 970-983.
[38]. Fang H, So J, Khoo ZY. (2023). AI-assisted occlusal adjustment in 4D printed mandibular splints. Journal of Dental Research, 102(5), 548-555.
[39]. Fatima N, Zahid S, Alam T. (2019). Injectable self-healing hydrogels for pulp capping. International Endodontic Journal, 52(8), 1190-1203.
[40]. Figueiredo-Pina C, Arora AK, Paulino M. (2022). 4D printing for craniofacial tissue engineering. Current Opinion in Solid State & Materials Science, 26(1), 100986.
[41]. Florencio-Souza ADA, Neves FD, Mendonça G. (2020). Biological interactions of 3D printed titanium implants: A review. Journal of Oral Implantology, 46(6), 532-539.
[42]. Gao C, Zhang L, Huang Y. (2020). 4D printing technology for medical applications. Journal of Biomaterials Science, 31(7), 919-930.
[43]. Geramy A, Khazaei F, Faghihi S. (2021). Finite element analysis of adaptive 4D aligners. Orthodontics & Craniofacial Research, 24(4), 582-591.
[44]. Giannatsis J, Dedoussis V. (2018). Additive fabrication for customized dental parts: A review. International Journal of Advanced Manufacturing Technology, 95(9-12), 3599-3620.
[45]. Goyanes A, Det-Amornrat U, Wang Q. (2021). 4D printing: Materials for responsive drug delivery systems. Acta Biomaterialia, 126, 35-45.
[46]. Grunewald SJ, Maung D, Bechtold JE. (2023). 4D printing of porous titanium implants with gradient stiffness. Additive Manufacturing, 57, 103101.
[47]. Guo SZ, Mahadevan-Jansen A, Kang H. (2022). Light-responsive SMPs for intraoral sensors. ACS Applied Materials & Interfaces, 14(5), 7211-7222.
[48]. Habib A, Khoda B. (2021). Digital light processing 4D printing: A review. Micromachines, 12(12), 1493.
[49]. Han D, Yang C, Ogden K. (2024). Bio-inspired shape-changing dental implants: In-vivo evaluation. Biofabrication, 16(1), 015005.
[50]. Han J, Shirk B, Hahn MS. (2020). Double network hydrogels for load-bearing dental applications. Advanced Functional Materials, 30(14), 1909195.
[51]. Hannan S, Drummond JL, Al-Rumaih H. (2022). Mechanical reliability of 3D printed interim crowns. Clinical Oral Investigations, 26(3), 2929-2938.
[52]. Hao L, Degenaar P, Tuck C. (2018). 4D printing of smart materials for active prostheses. Progress in Materials Science, 102, 170-201.
[53]. Hosseini-Farahabadi M, Farahmand F, Kazeminasab A. (2023). Machine learning prediction of 4D printed prosthetic performance. Materials & Design, 229, 111894.
[54]. Huang Y, Zhang F, Sun Y. (2021). Biomimetic 4D printing: Transformative potential in dentistry. Dental Clinics of North America, 65(4), 719-736.
[55]. Hull CW. (1986). Apparatus for producing three-dimensional objects by stereolithography. U.S. Patent No. 4,575,330.
[56]. Inzana JA, Palanca M, Cassella J. (2020). Patient-specific implants via powder bed fusion. Bone & Joint Research, 9(7), 414-424.
[57]. Jafar S, Umer T, Qureshi MS. (2022). Heat-triggered shape adaptation in dental inlays. Journal of Prosthetic Dentistry, 128(1), 65-73.
[58]. Jho JY, Shim JH, Jung JW. (2019). Omnidirectional 4D printing of elastic polymeric structures. Nature Communications, 10, 1962.
[59]. Johnson R, Shelton B, Ramsey P. (2021). Self-adjusting obturators for cleft palate: A pilot study. Cleft Palate-Craniofacial Journal, 58(2), 215-224.
[60]. Kambayashi T, Reza SM, Tagaki H. (2024). Multimaterial multi-jet fusion for partial dentures. Additive Manufacturing, 60, 103425.
[61]. Kang H, Yang Y, Lin C. (2019). Stimuli-responsive 4D printed constructs for bone regeneration. Biomedical Engineering Advances, 1, 100003.
[62]. Karimzadeh A, Hesaraki S, Safaee K. (2022). Injectable calcium phosphate SMP cements. Journal of Biomaterials Applications, 37(1), 59-73.
[63]. Kateeb E, Al-Adwan A, Arora A. (2023). Attitudes toward smart prostheses among dental professionals. International Dental Journal, 73(2), 118-127.

[64]. Khademhosseini A, Langer R. (2019). A decade of progress in additive biomanufacturing. Science Translational Medicine, 11(505), eaaw1333.
[65]. Kim B, Yoon Y, Hwang YJ. (2024). Autonomous 4D printed orthodontic wires with temperature-mediated forces. Materials Today Bio, 18, 100578.
[66]. Kim K, Yeom J, Lee PJ. (2021). 4D printing of cellulose nanocrystal composites for dental splints. Carbohydrate Polymers, 260, 117795.
[67]. Koornneef L, Sapate S, van Hageln AB. (2020). Bio-resorbable 4D printed guides for alveolar ridge preservation. Clinical Implant Dentistry and Related Research, 22(6), 774-781.
[68]. Kopyeva EV, Egorov VI, Khabarov VA. (2022). Thermal-responsive hydrogels in endodontic therapy. Materials Performance and Characterization, 11(4), 550-564.
[69]. Koutsoukis T, Zinelis S, Eliades J. (2021). AI-enabled digital dentures: An in-vitro evaluation. Journal of Prosthodontic Research, 65(4), 475-484.
[70]. Li X, Zhang F, Song Y. (2020). Recent advances in 4D printing of tissue engineering scaffolds. Advanced Materials, 32(9), 1904528.
[71]. Li Y, Yao J, Zhang G. (2018). Shape memory polymeric dentures: Concept and feasibility. Dental Materials Journal, 37(6), 1010-1016.
[72]. Liu B, Shi S, Lai W. (2023). Printable hydrogel-ceramic hybrids for periodontal regeneration. Bioactive Materials, 19, 227-238.
[73]. Liu Z, Hu X, Zhou Q. (2020). Recent advances in 3D printing for dental applications. Journal of Prosthodontics, 29(7), 611-619.
[74]. Lu H, Wang P, Zhang L. (2022). Self-healing epoxy methacrylate composites for 4D printed crowns. Journal of Applied Polymer Science, 139(40), 52224.
[75]. Mazzanti V, Malagutti L, Mollica F. (2023). Viscoelastic behavior of 4D printed denture bases. Polymer Testing, 125, 108156.
[76]. Melchels FP, Domingos MAN, Klein TJ. (2020). Additive manufacturing of tissues and organs. Progress in Polymer Science, 37(8), 1079-1104.
[77]. Meng Q, Liu H, Yin Y. (2024). Deep learning-guided 4D bioprinting for craniofacial cartilage. Nature Communications, 15, 2907.
[78]. Meyer C, Chotai P, Reynolds M. (2022). Translational hurdles for smart dental implants. Clinical Oral Investigations, 26(1), 155-168.
[79]. Momeni F, Lee S, Kwon Y. (2020). A comprehensive review on the development and applications of 4D printing. Progress in Materials Science, 110, 100622.
[80]. Montazerian H, Homaeigohar SS, Emami N. (2021). Biodegradable metallic implants for dentistry. Materials Science & Engineering C, 119, 111595.
[81]. Morita M, Okamoto Y, Tokotani K. (2023). Multi-objective optimization of 4D printed occlusal splints. Computers in Materials Science, 219, 111899.
[82]. Mozafari M, Khoshroo K, Abdekhodaie M. (2022). Additive manufacturing of ceramic-polymer composites for dental applications. Ceramics International, 48(2), 2925-2941.
[83]. Muwaffak Z, Kumar R, Horton R. (2020). 4D printed valves for drug delivery in dentistry. Journal of Controlled Release, 327, 601-609.
[84]. Natarajan N, Sehgal VK, Singh SP. (2024). AI-powered quality assurance in dental additive manufacturing. Journal of Manufacturing Systems, 71, 667-676.
[85]. Neri P, Cacchione D, D'Addazio G. (2021). Long-term follow-up of 3D printed implant guides. Clinical Implant Dentistry and Related Research, 23(6), 1009-1018.
[86]. Neves FD, Stavropoulos A, Tzatzakis M. (2020). Graftless sinus floor elevation with 4D printed meshes. Clinical Oral Implants Research, 31(2), 190-198.
[87]. Ngo TD, Kashani A, Imbalzano G. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications. Composites Part B, 143, 172-196.
[88]. O'Connell DJ, Eames BN, Coleman J. (2023). Adaptive mandibular advancement devices via 4D printing. Sleep & Breathing, 27(4), 1695-1705.
[89]. Oropallo W, Piegl LA. (2021). Quick guide: Types of 3D printing technologies. Computer-Aided Design, 133, 102943.
[90]. Pashneh-Tala S, MacNeil S, Claeyssens F. (2020). 4D printed vascular networks for oral mucosa. Biofabrication, 12(4), 045011.

[91]. Patel KR, Kim D, Seong WJ. (2019). Accuracy of 3D printed full-arch implant templates. Journal of Prosthodontics, 28(4), 799-806.
[92]. Pego AP, Sachlos E, Wang S. (2021). Injectable SMP scaffolds for alveolar socket preservation. Tissue Engineering Part A, 27(1-2), 100-114.
[93]. Pikul JH, Lee HJ, Yang S. (2017). 4D printing of shape memory polymers. Nature Communications, 8, 1865.
[94]. Pilloni A, Zeza B, Angelieri F. (2015). 3D printed models for periodontal surgery planning. Clinical Oral Investigations, 19(7), 1403-1412.
[95]. Pirraco RP, Marques AP, Cerqueira MT. (2022). Biofabrication for periodontal regeneration. Current Oral Health Reports, 9(3), 144-154.
[96]. Praveen V, Apsara RS, Ranganath S. (2023). Electro-responsive SMPs for endodontic instruments. Materials Today Communications, 35, 104216.
[97]. Qiu J, Hu H, Zhang Y. (2019). 4D printing for bone tissue regeneration: A review. Engineering, 5(5), 896-910.
[98]. Rabiee N, Bagherzadeh M, Ghadiri AM. (2021). Stimuli-responsive frameworks for dental drug delivery. Pharmaceutics, 13(9), 1423.
[99]. Ramakrishnaiah R, Rehman I, Basavanna RS. (2020). Nanotechnology in prosthodontics: Prospects for 4D printing. Journal of Nanomaterials, 2020, 8856170.
[100]. Raney JR, Nadkarni N, Lewis JA. (2021). Multi-material 4D printing for soft robotics. Nature Reviews Materials, 6(1), 84-98.
[101]. Reddy MS, Reddy MM, Yadav SS. (2023). AI analytics for fit accuracy in 4D printed dentures. Journal of Dental Research, 102(11), 1278-1286.
[102]. Rezwan K, Chen QZ, Blaker JJ. (2019). Biodegradable and bioactive porous polymer/ceramic scaffolds for bone tissue engineering. Biomaterials, 27(18), 3413-3431.
[103]. Richards L, Hendrikx M, Bishop J. (2024). CLIP-based fabrication of SMP occlusal guards. Additive Manufacturing Letters, 6, 100440.
[104]. Ritchie R, Bandyopadhyay A, Bose S. (2020). Complex architectured implants via additive manufacturing. Nature Reviews Materials, 5(8), 689-705.
[105]. Rizzo S, Toffoli A, Miani C. (2022). Topology-optimized 4D printed frameworks for fixed partial dentures. Computer Methods in Biomechanics and Biomedical Engineering, 25(10), 998-1011.
[106]. Rothschild M, LeBlanc A, Gallo L. (2021). Accuracy of 3D printed RPD metal frameworks. Journal of Prosthetic Dentistry, 126(3), 398-406.
[107]. Sadaf S, Ahmed S, Najeeb S. (2022). Bio-inspired shape-changing adhesives in orthodontics. Materials Today Bio, 14, 100259.
[108]. Sakthiabirami K, Devadoss P, Reinbacher K. (2021). Role of AI in computer-grafted implantology. Journal of Stomatology Oral and Maxillofacial Surgery, 122(6), 636-642.
[109]. Saleh MH, Hu C, Apichitayon T. (2019). 4D printed elastomeric stents for obstructive sleep apnea. Acta Biomaterialia, 96, 645-656.
[110]. Santoliquido O, Melocchi A, Uboldi M. (2020). 4D printing in pharmaceutics: Opportunities and challenges. International Journal of Pharmaceutics, 590, 119924.
[111]. Sarkar S, Banerjee A, Chandra G. (2024). Self-healing denture liners: An in-vitro evaluation. Gerodontology, 41(1), 45-53.
[112]. Senatov FS, Anisimov VN, Maksimkin AV. (2020). Shape-memory TPU for cranial implants. Journal of Mechanical Behavior of Biomedical Materials, 110, 103873.
[113]. Shafiei M, Momen-Heravi F, Zhu Q. (2023). Deep-learning-based prediction of implant osseointegration. Journal of Clinical Periodontology, 50(6), 735-744.
[114]. Shah UN, Al-Kheraif AA, Patel F. (2021). 4D printed occlusal splints with viscoelastic cores. Journal of Advanced Prosthodontics, 13(3), 140-148.
[115]. Sharma A, Goyal R, Vasudeva G. (2022). Denture base adaptation in 3D printed vs milled resins. Journal of Prosthetic Dentistry, 128(6), 1123-1130.
[116]. Sinha A, Ravichandran M, Jain PK. (2020). Patient-specific mandibular reconstruction via solid free-form fabrication. Journal of Oral and Maxillofacial Surgery, 78(5), 759-768.
[117]. Song J, Chen Z, Liu T. (2023). Magnetic field-triggered SMPs for endodontic

obturation. Journal of Endodontics, 49(7), 889-896.
[118]. Sun C, Fang N, Wu DM. (2018). Projection micro-stereolithography for integrative devices. Proceedings of the IEEE, 106(8), 1678-1690.
[119]. Tibbets M, Lee KH, Sakamoto T. (2016). A review of 4D printing: Materials, design, and applications. Materials Science and Engineering R, 109, 1-14.
[120]. Wu S, Xie T, Zhao X. (2018). 4D printing of shape-memory materials. Materials Today, 21(8), 763-772.