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THE DIGITAL DENTITION: 3D PRINTING'S IMPACT ON ORTHODONTIC CARE

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Abstract: The future of 3 dimensional (3D) printing in orthodontics holds the potential to be nothing short of transformative, reshaping the landscape of dental care with unprecedented precision, efficiency, and customization. As technology advances, it is poised to revolutionize the design and manufacturing of orthodontic devices such as aligners, braces, and retainers—enabling treatments that are more precisely tailored to each patient's unique dental anatomy. With the ability to produce complex structures with remarkable accuracy, 3D printing promises faster turnaround times, reduced costs, and more effective, predictable treatment outcomes. This shift toward digital workflows—incorporating advanced scanning, modeling, and fabrication technologies—will streamline orthodontic processes, making them faster, more efficient, and better suited to individual patient needs. The result will be enhanced patient satisfaction and superior clinical outcomes, with practitioners offering a level of personalization previously unimaginable. Embracing this technological evolution is essential for orthodontic professionals committed to staying at the forefront of their field, redefining care standards, and providing patients with the most precise, efficient, and personalized treatments available.

Keywords: Aligners, Customization, Digital workflows, Orthodontics, Precision, 3D printing

Introduction: The digital age has transformed many industries, and orthodontics is no exception, with 3D printing at the forefront of this revolution. 3D printing, or additive manufacturing, allows for the creation of customized dental appliances by layering materials based on digital models, offering unprecedented precision and personalization (1). This technology has significantly improved the production of orthodontic appliances, such as aligners, retainers, braces, and models for treatment planning (2). Historically, creating orthodontic appliances involved taking molds, a process that could be uncomfortable and prone to inaccuracies (3). However, with the advent of 3D printing, orthodontic professionals can now use digital impressions to create highly accurate models of a patient's teeth and jaws. This not only ensures a better fit but also enhances comfort for patients, making devices more personalized to their unique dental anatomy (4).The evolution of 3D printing, pioneered by Charles "Chuck" Hull in the 1980s, has led to faster, more precise, and cost-effective solutions in orthodontics. Hull's invention of the stereo lithographic 3D printer in 1986 marked the beginning of a technological transformation (5). Over time, new techniques such as Fused deposition modeling (FDM) by Scott Crump and inkjet printing for metal materials by Professor Ely Sachs in 1995 paved the way for the widespread use of 3D printing in various industries, including orthodontics (6).The key benefits of 3D printing in orthodontics include enhanced precision, reduced production costs, and faster manufacturing times. Traditional methods involved creating physical models from molds, which could take several weeks and lead to errors (7). With 3D printing, the process has become much more efficient, reducing the time between design and final product and minimizing patient wait times (8). Moreover, dental professionals can now produce custom appliances in-house, bypassing the need for external production, thus reducing costs. The rise of desktop 3D printers has made this technology more accessible, even to smaller practices, allowing them to offer high-quality, customized dental solutions (9). This accessibility has opened the door for enhanced patient care and streamlined orthodontic practices. Several 3D printing technologies are employed in orthodontics, each offering unique benefits. The most common types include **[Figure 1**] (10):

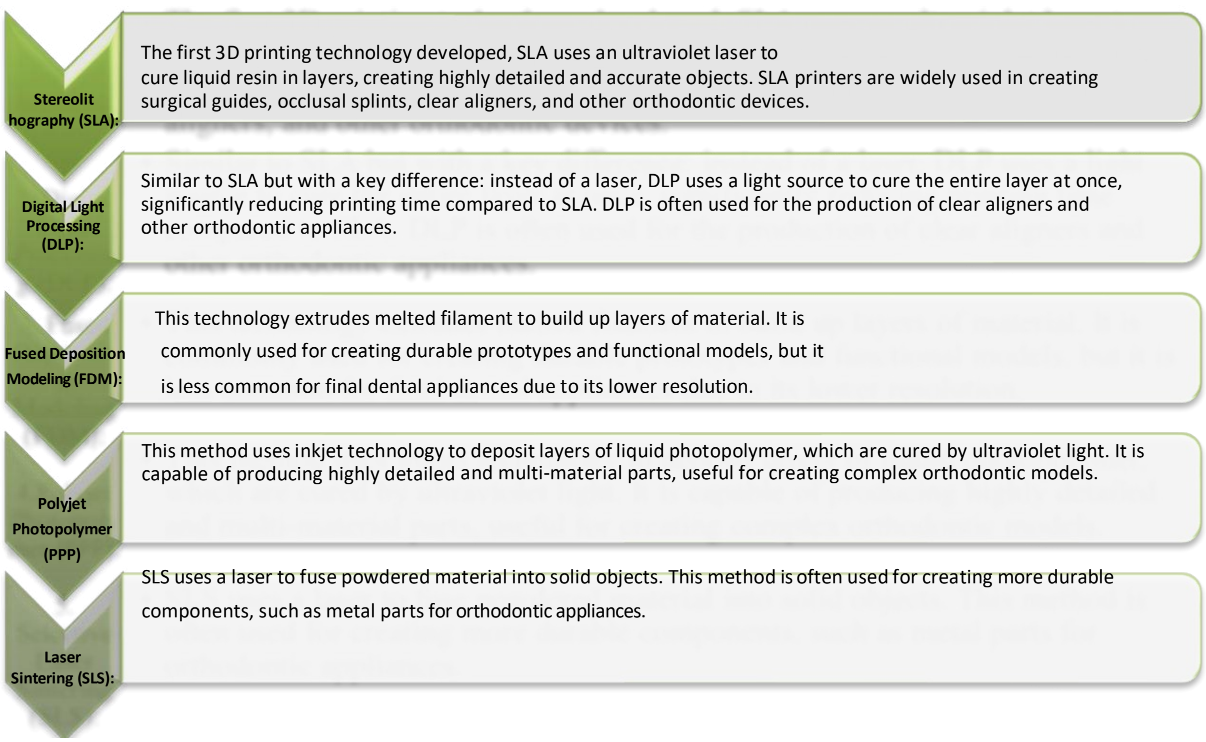

Figure 1: Types of 3D printers in orthodontics

3D printing is revolutionizing orthodontics by offering more precise, customized, and efficient solutions. However, challenges remain, particularly in developing materials that closely mimic the natural properties of teeth, such as enamel and dentin. Durability, appearance, and long-term wear are critical concerns for orthodontic devices (11). Additionally, improving printing speed without sacrificing quality is an ongoing challenge. The integration of artificial intelligence (AI) and bioprinting presents exciting possibilities for overcoming these hurdles (12). AI-guided orthodontic treatments and the potential for creating living tissues for dental implants could significantly enhance personalization and effectiveness in care (13). As 3D printing technology advances, it is reshaping orthodontics, providing less invasive, faster, and more efficient treatments. The continued development of AI, improved materials, and enhanced printing techniques will elevate the quality, durability, and precision of dental appliances. For dental professionals, staying current with these innovations—through collaboration with 3D printing companies and ongoing learning—is essential for improving patient outcomes and fostering future advancements. As 3D printing becomes more scalable and cost-effective, its widespread adoption will streamline production and distribution in orthodontics. Collaboration across sectors, including technology providers, dental practitioners, and research institutions, will drive innovation, while advancements in quality control, materials, and cyber security will ensure product safety and efficacy(14).

Ultimately, the continued growth of 3D printing in orthodontics promises not only to enhance patient care but also to promote sustainability through more efficient and eco-friendly practices. This technological evolution is poised to drive economic growth in the dental industry and shape the future of orthodontic treatment. This review highlights 3D printing's transformative impact on orthodontics, enhancing precision, customization, efficiency, and patient care while addressing challenges (15).

Research Methodology

Using a descriptive and exploratory research approach, this study examined how 3D printing affects orthodontic treatment with an emphasis on patient satisfaction, accuracy, cost-effectiveness, and efficiency. A mixed-methods approach was used in the technique, including literature studies, experimental data, and primary data gathered via surveys and interviews. This all-encompassed approach guarantees a full comprehension of how 3D printing is changing orthodontic procedures and results.

Data Collection

Experimental investigations compared the accuracy, efficiency, and usefulness of 3D-printed models with conventional cast models were used to gather primary data. Digital calipers and scanning software were used to build and assess orthodontic devices, included as aligners, brackets, and retainers, with an emphasis on clinical performance, accuracy, and patient comfort. The development of 3D printing technology, important variables influencing accuracy (such as resin shrinkage and polymerization speed), and experimental results were all examined in a study of peer-reviewed papers, case studies, and clinical trials.

Data Analysis

To evaluate accuracy, efficiency, and other performance metrics between conventional and 3D-printed models, quantitative data from the experimental research were statistically analyzed. Comparative analyses and tests of the significance of observed differences were conducted using software tools such as SPSS. N Vivo software were used to thematically analyze qualitative data from surveys and interviews in order to find common patterns, obstacles, and advantages related to the use of 3D printing in orthodontics.

Inclusion Criteria:

The use of 3D printing in orthodontics was the subject of studies, experiments, or participation. Orthodontic professionals who had worked with digital processes, such as 3D scanning and printing, for at least a year were involved. Patients aged 12 years or older who received orthodontic treatment with 3D-printed equipment (such as aligners, brackets, and retainers) participated in the studies. Case studies, clinical trials, and peer-reviewed publications were released in the last ten years (2014–2024). Tools and methods using widely used 3D printing technologies, including DLP, Continuous Liquid Interface

Production (CLIP), and SLA, were utilized. Research on tyhe variables that influenced the precision, effectiveness, and patient satisfaction of 3D printing was conducted.

Exclusion Criteria:

Research into 3D printing's non-orthodontic uses, such as maxillofacial surgery or prosthodontics, focused on orthodontic professionals who had never used 3D printing technology or digital processes before. It also involved patients with health issues unrelated to orthodontics that may have affected how well they responded to therapy. The research or articles were not subjected to peer review or were published before 2014. The 3D printing methods or materials—like industrial-grade materials—that were unrelated to orthodontics were examined.

Some studies did not provide enough information or did not directly compare conventional and 3D printing methods.

Prisma flowchart of the study has been shown in **[Figure 2]**

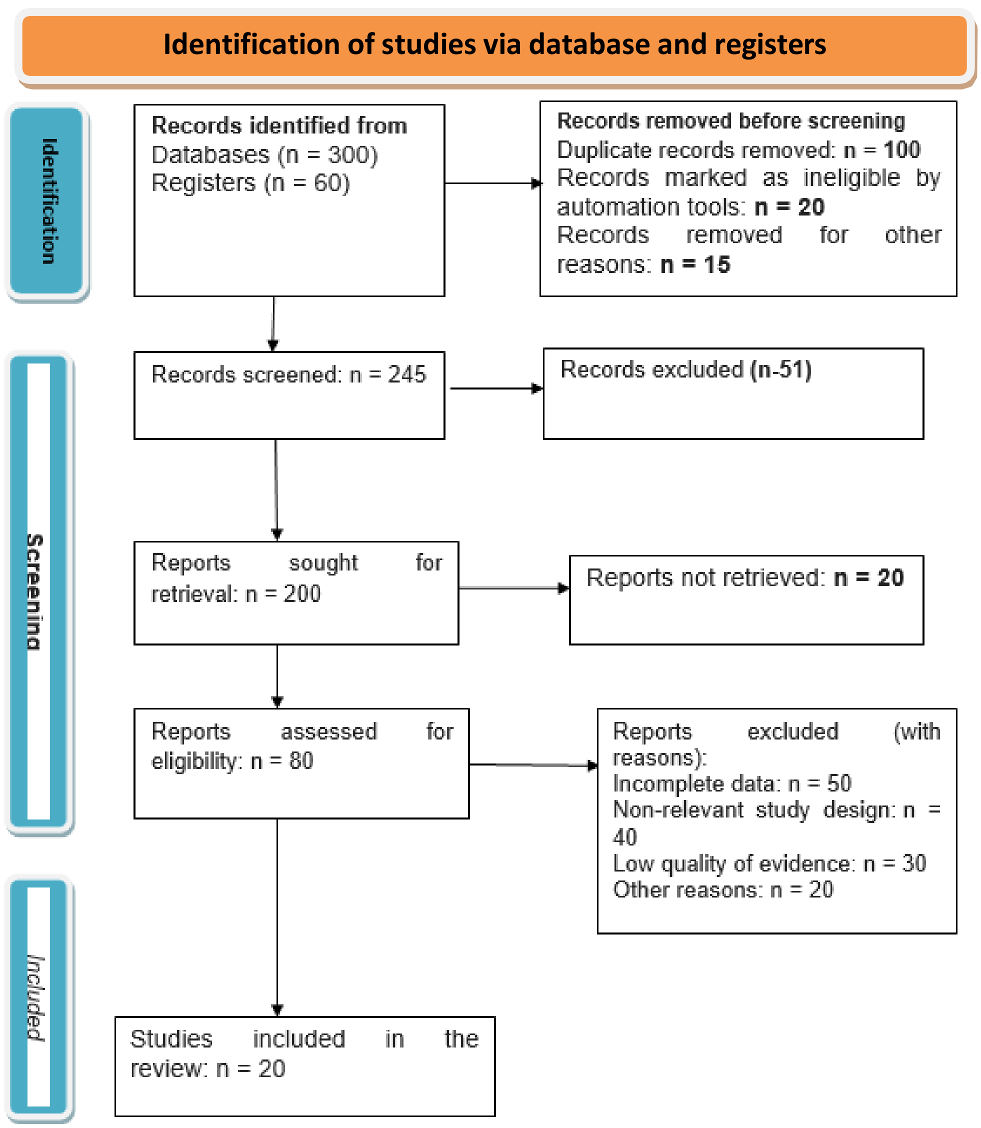

Figure 2: PRISMA flowchart

Discussion: In orthodontics, traditional cast models are bulky, challenging to store, and difficult to replicate, while digital models provide enhanced precision for arch alignment and tooth movement planning. 3D-printed replicas improve upon the accuracy of traditional stone models, and intraoral digital scans increase patient cooperation by eliminating the need for conventional impressions (16).In 3D orthodontics, cast models and digital models are two approaches used to capture and analyze a patient's dental anatomy for treatment planning. They each have distinct advantages and limitations, which can influence the choice depending on the clinical context. [**Table 1]** depicts key differences between cast models and digital models (17-20).

Table1: Comparison of cast models and digital models in 3D orthodontics

Feature	Cast models	Digital models
Definition	Physical 3D models made from impressions and plaster	Virtual 3D models created by digital scanning
Speed	Slow to create, takes more time	Fast to create, scan done in minutes
Accuracy	Can be less accurate due to distortion	Highly accurate and precise, less distortion
Storage	Takes up physical space, needs careful storage	Easy to store, can be saved digitally and accessed anytime
Patient comfort	Impressions can cause discomfort or gagging	More comfortable, no impression material needed
Advanced tools	Limited tools for analysis	Allows advanced software for treatment planning and simulations
Tactile feedback	Can be touched and felt for detailed examination	No tactile feedback, all viewed on a screen
Environmental impact	Uses plaster, alginate, or silicone that may not be eco-friendly	Minimal waste, no physical materials needed
Time-consuming	Takes longer due to impression and casting process	Quick scanning process saves time
Inaccuracies	Impressions can be distorted or inaccurate	Very precise and consistent
Cost	Generally cheaper to use	Expensive initial cost for scanners and software
Learning curve	Easy to use and familiar to most orthodontists	Requires training to use scanning systems and software
Technical issues	No technical issues (physical models)	Can encounter glitches or system issues

A study by Zhang et al. demonstrated that 3D-printed models with a 50 μm thickness were more accurate, with CLIP technology showing less variation compared to DLP (21). However, while traditional casts exhibited fewer volumetric changes, the 3D-printed models showed slightly lower accuracy in linear measurements, particularly in the posterior teeth. Despite these improvements, digital models have not completely supplanted conventional models (22). Accurate bracket placement, essential for optimal treatment, is enhanced by 3D-printed indirect bonding trays, which reduce working time and offer better precision compared to conventional poly vinyl siloxane trays, although they are less accurate for vertical transfers (23). CAD-CAM technology has also enabled the development of guided bonding tools that enhance bracket placement accuracy. 3D printing has revolutionized the production of orthodontic appliances, allowing for quicker and more precise fabrication of metal devices through laser metal sintering, reducing the dependence on traditional techniques like separator placement and impression taking (24). Common 3D-printed metal appliances include Hyrax-style rapid palatal expanders. Additive manufacturing has also made it possible to produce removable appliances such as Hawley's retainers, diagnostic tools, and personalized patient-specific brackets that improve treatment efficiency (25). Looking ahead, 3D workflows are expected to continue advancing orthodontics, including the creation of attachments for impacted teeth and fixed twin blocks. However, resin-based appliances must undergo biocompatibility and cytotoxicity testing to ensure their safety and long-term durability (26).

Factors affecting 3D printing accuracy: Dimensional inaccuracies in 3D printing are often caused by resin shrinkage during the process. The precision of 3D printed objects can be influenced by various factors, such as the speed and intensity of the polymerizing energy source, build direction and orientation, the positioning of objects on the platform, the arrangement of support structures, layer thickness, material shrinkage between layers, and post-processing methods **[Figure 3]** (27).

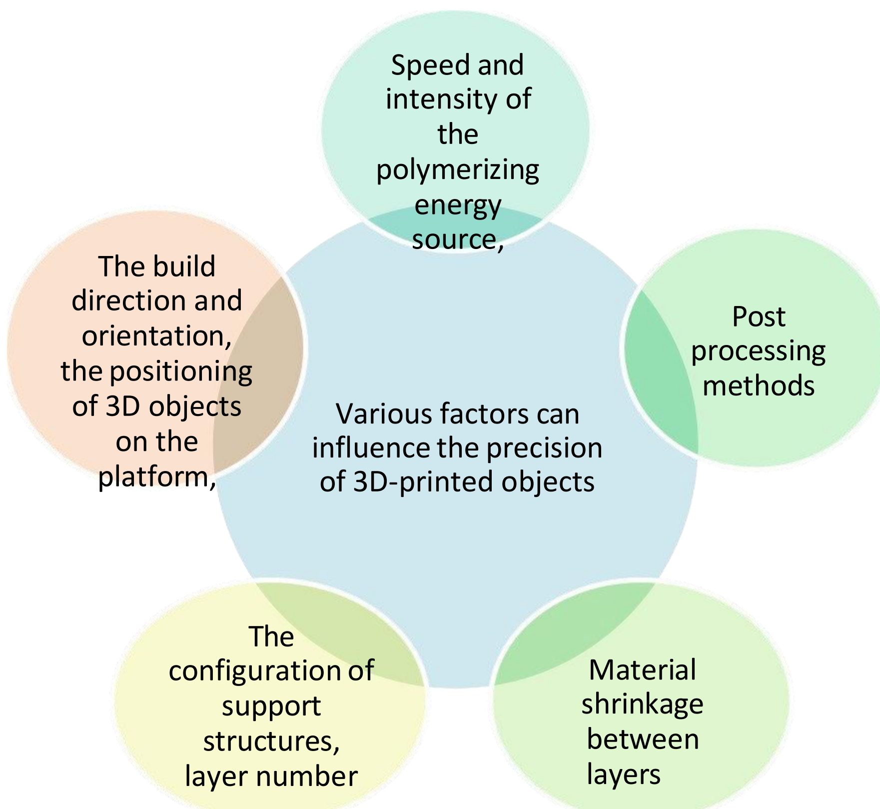

Figure 3: Factors affecting 3D print accuracy

Build Orientation: The accuracy and biocompatibility of 3D-printed products can be influenced by their build orientation. For instance, Gao et al. tested mandibular dentures at various angles and found that a

45° orientation yielded the most precise results (28). Similarly, Quintana et al. observed that the tensile stress and elasticity modulus of SLA-fabricated samples were dependent on the build orientation, with compressive strength being higher when layers were printed perpendicular to the applied load (29). On the other hand, Edelmann et al. reported that neither print orientation nor post-print curing had a notable effect on the precision of 3D-printed aligners (30). Additionally, Ko et al. identified a statistically significant interaction between 3D-printed model accuracy, build angle, and layer height (31).

Layer thickness: The optimal layer thickness can vary depending on the 3D printing method used. While using fewer, thicker layers can speed up the printing process, it may reduce the level of precision. Studies have shown that using smaller layers with SLA technology can enhance the strength of the printed samples (32). Chock Lingam et al. concluded that a layer thickness of 100 µm was ideal for achieving the best results with a post-curing time of 60 minutes and vertical orientation (33). Similarly, Loflin et al. found that a 100 µm layer thickness provided optimal outcomes for orthodontic samples (34).

Infill ratio: The infill ratio indicates the proportion of solid material within a 3D-printed object. In FDM, this ratio is adjusted by modifying the gap between the printed lines, which plays a crucial role in the printing process, more so than in other techniques (35). As Milde et al. explain, the infill percentage has a substantial impact on the compressive strength of FDM-printed items. Increased infill percentages improve strength, although when the infill rate is low, the design and structural considerations become more important for maintaining strength (36).

Post-processing: It can improve the performance of printed samples, though it requires additional time and resources. Shrinkage and distortion of resin materials during SLA printing can be minimized through post-curing techniques, such as ultraviolet (UV) or microwave exposure, which enhance the material's elasticity and overall strength. Moreover, increasing the laser intensity can further bolster the printed sample's strength (37).

Circular economy in 3D printing: While 3D printing focuses on precision and minimal waste, some degree of waste production is unavoidable in dental applications. The exact amount of waste generated from 3D printing in dentistry is not yet well-defined due to the technology's emerging nature. Examples of this waste include support structures used to prevent deformation and multiple 3D-printed models created during virtual design. Minimizing waste and advancing a circular economy is vital. One approach to this is recycling; however, there is limited data on recycling 3D printing waste. Common physical recycling techniques, such as shredding and reprocessing via melting or high-temperature decomposition, present challenges. Developing biodegradable polymers or using catalysts/solvents to assist in the degradation of 3D-printed dental products may offer a more sustainable alternative (38).

Micro-electronic sensors for monitoring compliance: Micro-electronic sensors for tracking patient compliance have been effectively integrated into various devices, such as those used for sleep disorders, facemasks, active removable appliances, and long-term retainers in post-orthodontic treatment. These sensors are crucial for monitoring adherence to treatment protocols. Wearable technologies provide continuous, unobtrusive, and objective tracking of compliance, as well as the assessment of sleep disorders, jaw function, and parafunction using advanced 3D printed appliances (39). Devices that are lightweight and unobtrusive are keys for monitoring mandibular movement in natural settings, and when paired with micro sensors, they can help assess compliance in patients with obstructive sleep apnea. Although 3D printed orthodontic brackets, which incorporate light emitting diode (LED) lights and batteries to support bone regeneration, are still in the early stages of development, they show promise for future clinical use, pending further research and trials (40). Additionally, simulations and advanced software can assist dentists in creating more precise and innovative appliances. This is just the beginning, and the potential for 3D printing in dentistry is vast, with many exciting developments still to come (41).

Expanding applications of 3D printing in dentistry: A diverse array of 3D printed dental products is now accessible, including surgical instruments, night guards, and beyond. Orthodontics is rapidly embracing innovative materials and advanced technologies, turning the fully equipped 3D orthodontic clinic into a tangible reality. The integration of state-of-the-art tools like intraoral and facial scanners, digital X-rays, cone beam computed tomography (CBCT), and additive manufacturing has greatly enhanced treatment effectiveness, precision, consistency, and predictability (42).

Types of 3D printed appliances for orthodontic practices:

Orthodontic models: Digital models offer high validity, reliability, and reproducibility, making them a viable alternative to traditional plaster models. Rapid prototyping technology ensures multiple identical copies of a digital model without distortion or deformation. These printed models can be used for diagnostics, treatment planning, and manufacturing removable orthodontic devices, including aligners and retainers (43).

Removable orthodontic appliances: This category encompasses a range of devices, including the simple Hawley retainer, more complex functional appliances like the activator and Twin Block, as well as sleep apnea devices. Pioneering work by Sassani et al. explored the use of Computer-aided design (CAD) and 3D printing in the creation of removable acrylic orthodontic appliances (44). Further advancements include the production of Hawley retainers using intraoral scans obtained with TRIOS™ (3Shape), which eliminates the need for conventional impression methods (45).

Pre-surgical nasoalveolar moulding (PNAM): The integration of digital technologies has also impacted treatments for patients with cleft lip and palate. CAD software allows clinicians to create appliances with greater efficiency, while reducing patient visits and treatment time. Shen et al. used CAD and 3D printing to design orthopedic devices based on Grayson and Cutting's treatment protocol, yielding comparable results to traditional methods but with fewer clinic visits (46).

Occlusal splints: Modern occlusal splints, used for temporomandibular disorders and asymmetries, are increasingly being manufactured using digital workflows. While initial work has used subtractive methods, 3D printed occlusal splints still require further clinical and scientific evaluation (47).

Surgical templates for orthodontic miniscrews and miniplates: 3D printed surgical guides for the accurate placement of orthodontic miniscrews and miniplates have been created, along with techniques for tailoring miniplates through CAD and CBCT-based printed models (48).

Anchorage reinforcement devices and space maintainers: These devices, used in interceptive orthodontics to prevent or address malocclusions in children, are now being fabricated using 3D metal printing. Examples include the transpalatal arch, hybrid Nance appliance, and lingual arch (49).

Expansion appliances: Devices like rapid palatal expanders can be designed in various configurations and 3D printed for efficient treatment. Complex devices like the 3D printed Hyrax-Hayrake-Blue-grass combination appliance offer a mix of appliances for multiple treatment purposes (50).

Fixed orthodontic appliances: Personalized, patient-specific orthodontic brackets are transforming treatment approaches. Companies such as light force orthodontics are leading the way by providing 3D printed brackets with optimized geometries to enhance tooth movement efficiency. Additionally, self-ligating and lingual brackets, as well as indirect bonding trays, are also customized using 3D printing technology (51).

Mandibular positioning devices: Appliances like the Herbst device for anterior mandibular repositioning are now produced using 3D metal printing, ensuring precision and efficiency in orthodontic care (52).

Clear aligners: By utilizing CAD software, orthodontists can create a series of aligners to achieve gradual tooth movement. Directly printed aligners crafted from materials such as dental light transmitting resin, provide benefits like excellent shape retention at elevated temperatures and enhanced durability in clinical use (53).

Retainers: Clear and thermoformed retainers, commonly used in orthodontic practice, can be 3D printed with remarkable accuracy. Fixed lingual retainers, also 3D printed, provide superior customization (54).

Recent advancements in 3D printing for orthodontics: The potential of 3D printing in orthodontics has expanded considerably, enabling more personalized treatment through the integration of advanced digital technologies. What was once a topic of debate has now become a cornerstone of modern orthodontic practices. With ongoing advancements in the field, exciting innovations are emerging, such as the integration of micro-electronic sensors into orthodontic appliances (55). These sensors enable continuous monitoring of patient compliance, sleep disorders, and jaw function. The trend toward lightweight and discreet wearable devices is enhancing patient care and improving overall treatment outcomes. Various studies highlight the diverse range of 3D-printed devices that have undergone clinical trials, though few studies have rigorously evaluated their clinical effectiveness (56). Various researches reviewed various 3D printing methods, including SLA, DLP, FDM, SLS, and binder jetting. SLA and DLP emerged as the most commonly used techniques, while the most frequently printed devices included models (55.5%), indirect bonding trays (19%), surgical splints for orthognathic surgery (16%), and direct-printed aligners (8%) (57).

Around 91% of the studies concentrated on assessing the accuracy of 3D printers, primarily by evaluating trueness and precision through comparisons of STL data from reference and experimental models (58). Methods such as model analysis, linear and angular measurements, and occlusal fit were commonly used to evaluate accuracy. Overall, 3D printing has proven to streamline the production of orthodontic devices, offering improved precision (59). Tsolakis et al. reported that polyjet photopolymer technology achieved the highest accuracy, with minimal influence from layer height or model positioning (60). The study also found that 3D-printed clear aligners outperformed thermoformed ones in terms of accuracy, load resistance, and reduced deformation. Digital occlusal splints and surgical templates were also found to be more accurate, reliable, and efficient compared to conventional versions. Although digital and 3D-printed models have not entirely replaced traditional casts, they offer notable advantages in precision and efficiency (61). The accuracy of 3D-printed models is influenced by the type of printer and technology employed, emphasizing the importance of optimal design and post processing techniques to enhance strength and precision. Studies suggest that a layer thickness of 100 µm is ideal for achieving the best results (62). These findings reflect ongoing advancements in 3D printing for orthodontics, underscoring the technology's potential to improve treatment precision, efficiency, and customization. As the technology continues to develop, the future of orthodontics is likely to see more widespread integration of 3D printing for everything from appliances to brackets, leading to even better treatment outcomes (63). **[Table 2]** summarizes key studies related to the use of 3D printing in orthodontics.

Table 2: Key studies on 3D printing in orthodontics

Study	Key focus	Findings/results	Implications for the future
Zhang et al. (2024) (64)	Accuracy of 3D-printed models	Found that 3D-printed models were accurate at a 50 µm thickness with lower variability in CLIP compared to DLP printing	Suggests improved accuracy and reliability of 3D models for treatment planning
Plattner et al. (2023) (65)	3D-printed trays vs. traditional trays	3D-printed trays reduced working time and were more precise than conventional Poly vinyl siloxane trays, except for vertical transfers	Demonstrates that 3D printing improves efficiency and precision in orthodontic indirect bonding procedures
Chaudhary et al. (2022) (66)	Precision of 3D-printed trays	Confirmed that 3D-printed trays provided more accuracy in horizontal transfers than traditional methods	Highlights the potential for customization and improved bracket placement in orthodontics.

Xue et al. (2023) (67)	CAD-CAM in guided bonding tools	Developed a CAD-CAM system for precise bracket transfer using 3D-printed trays	Future orthodontic workflows will integrate CAD-CAM with 3D printing to enhance accuracy in bracket placement.
Bachour et al. (2022) (68)	Linear vs. angular measurement accuracy in 3D-printed trays	Found that 3D-printed trays were accurate for linear measurements but less precise for angular measurements	Suggests the need for refinement in angular measurements, but confirms significant potential in linear applications.
Sassani et al. (2021) (69)	Removable acrylic orthodontic appliances	First demonstration of CAD-CAM removable orthodontic appliances with 3D printing technology	Paves the way for fully customized, 3D-printed removable appliances like retainers
Al Moradi et al. (2024) (70)	Use of 3D Printing in sleep apnea devices and activators	Created andresen activators and sleep apnea appliances using CAD and 3D printing	Demonstrates versatility in orthodontics, with applications extending to non-traditional devices like sleep apnea gear
SLS technology studies (71)	3D-printed metal appliances using laser sintering	SLS used for creating metal orthodontic appliances such as palatal expanders	Revolutionizes metal appliance manufacturing, improving precision and speed in creating complex appliances
Hyrax expansion studies (72)	3D-printed hyrax-style rapid palatal expansion appliances	3D-printed hyrax expanders demonstrated efficient and rapid fabrication for orthodontic treatments	Future orthodontics could benefit from faster, more customizable palatal expansion devices with 3D printing
Light-force orthodontics studies (73)	3D printing of custom braces for tooth alignment	Custom braces designed using 3D printing technology allowed for more efficient tooth movement	Future treatments will rely more on personalized, 3D-printed brackets for optimized tooth movement and faster results

Future prospects:

The future of 3D printing in orthodontics is incredibly promising, with continuous advancements in technology, materials, and digital integration. Here are the key prospects shaping the future of 3D printing in orthodontics:

1. **Enhanced customization and personalization**
    - Precision tailoring: Advancements in scanning and digital impressions will allow orthodontists to create highly customized appliances tailored to each patient's unique anatomy and needs. This will enhance the fit, performance, and treatment efficiency of aligners, braces, and retainers.
    - AI integration: AI will play a pivotal role in analyzing scans and automatically designing personalized treatment plans, further improving the precision of orthodontic devices and optimizing workflows (74).
2. **Faster production and reduced costs**
    - On-demand manufacturing: 3D printing allows for on-demand production of orthodontic devices, eliminating the need for inventory management and reducing costs related to materials, labor, and storage.
    - Speed of production: The time required to produce orthodontic appliances will continue to shrink, with advancements in printing speed enabling the creation of functional dental devices in a matter of hours, improving patient satisfaction and turnaround time (75).
3. **Innovative materials and functional advancements**
    - Smart materials: Future 3D printed orthodontic devices will likely incorporate smart materials that respond to environmental stimuli like temperature, pressure, or moisture. These materials will enable dynamic, adaptive appliances that adjust during treatment for optimal effectiveness.
    - Bioprinting: The potential of bioprinting to create living tissues opens exciting possibilities for regenerating tooth and gingival tissue, which could lead to revolutionary treatments like tooth regeneration and gingival restoration (76).
4. **Improved treatment outcomes**
    - Enhanced devices: 3D printing will continue to improve the design and functionality of orthodontic devices, making them lighter, thinner, more flexible, and more comfortable for patients, all while delivering better treatment outcomes.
    - Real-time adjustments: Digital scanning and 3D printing will enable orthodontists to make immediate adjustments to aligners or braces, reducing the need for multiple appointments and accelerating treatment timelines (77).
5. **Integration with other digital technologies**
    - Seamless digital workflow: Integration between intraoral scanners, CAD/CAM systems, and 3D printers will streamline the entire process, from diagnosis to appliance production, eliminating manual steps and improving both accuracy and efficiency.
    - Virtual treatment simulation: Virtual and augmented reality will enhance patient care by allowing them to visualize their treatment progress in 3D before it begins, supporting better decision-making and treatment planning (78).
6. **Regenerative dentistry and tissue engineering**
    - Regenerating teeth and gingiva: Bioprinting may allow for the direct creation of dental structures such as teeth and gingiva, offering a potential solution for patients who need tooth replacements or gingival regeneration, reducing reliance on implants or traditional prostheses.
    - Stem cell applications: Stem cell-based bioprinting could allow the regeneration of dental tissues, providing a more sustainable and less invasive approach to orthodontic and dental treatments (79).

7. Environmental sustainability

- Reduced waste: 3D printing's layer-by-layer approach produces minimal waste compared to traditional manufacturing methods, making it more environmentally friendly.

- Eco-friendly materials: The future may see the development of biodegradable and recyclable materials for 3D printed orthodontic devices, contributing to sustainability in the dental industry (80).

8. **Wider accessibility and training**
   - Global reach: The decreasing cost of 3D printers and materials will make advanced orthodontic care more accessible in underserved regions, enabling smaller practices to offer customized treatments.
   - Ongoing training: As 3D printing technologies evolve, continuous training will be necessary for orthodontists to stay up-to-date with the latest tools, materials, and digital workflows.

9. Teleorthodontics and remote care
   - Remote monitoring: Digital scans and 3D models will enable orthodontists to monitor patients remotely, offering more flexible and efficient care for patients who are distant or unable to visit clinics frequently.
   - Direct-to-consumer models: The future may bring more direct-to-consumer orthodontic services, where patients can receive 3D printed aligners based on digital impressions taken at home, reducing the need for in-person visits and lowering costs.

The promise of 4D Printing:

Looking even further ahead, 4D printing could revolutionize orthodontics by enabling self-adjusting devices that respond to external stimuli, such as temperature or pressure. This could lead to appliances that dynamically adapt to the patient's needs throughout the treatment, offering a new level of customization and efficiency in orthodontic care. In conclusion, the future of 3D printing in orthodontics is filled with endless possibilities, from faster production and reduced costs to groundbreaking innovations in smart materials, regenerative dentistry, and remote care. As technology continues to advance, 3D printing will reshape the way orthodontic care is delivered, making it more efficient, accessible, and personalized (81).

Conclusion: In the next decade, 3D printing in orthodontics will transform treatments, making them faster, more affordable, and personalized. Advancements in materials, AI, and bioprinting will lead to custom, efficient, and less invasive options. Digital workflows and 3D printing will enhance patient outcomes while improving practice efficiency. Orthodontists are increasingly adopting 3D printing, with technologies like SLA, DLP, FDM, and PolyJet being commonly used. While these technologies show similar or better accuracy than traditional models, more research is needed to determine the most efficient for different orthodontic procedures. The ability to eliminate conventional impressions and models will reduce storage needs and improve appliance fit. Future efforts should focus on developing biodegradable polymers and eco-friendly solutions to address environmental concerns with 3D printing.

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References:

1. Melchels FPW, Feijen J, Hermans M, et al. A review on 3D printing techniques in tissue engineering. J Biomed Mater Res B Appl Biomater. 2010; 102(4): 993–1002.

2. Mavrogiannis M, Schätzle M, Lagravère MO, et al. The role of 3D printing in the treatment of dental malocclusions. Orthod Craniofacial Res. 2018; 21(2):110-115.

3. Parikh K, Mehta D, Bhagat S. Current trends and future advancements in 3D printing for orthodontic appliances. J Orthod. 2019; 46(4):312-318.

4. Cehreli ZC, Ozdemir T, Tuncer D. Additive manufacturing technologies and their application in orthodontics. Eur J Orthod. 2020; 42(1):85-94.

5. Hsu JY, Lee JH, Park JB, et al. The use of 3D printing in orthodontic research and clinical practice. J Dent Sci. 2021; 16(3):1075-1080.

6. Balsa R, Barroso L, Lanza F, et al. 3D printing in orthodontics: current technologies and future directions. J Clin Orthod. 2017; 51(7):442-450.

7. Zogbi L, Kouri A, O'Brien J, et al. 3D printing and its potential role in orthodontics. Am J Orthod Dentofacial Orthop. 2018; 153(3):420-428.

8. Boeddinghaus M, Kravitz ND, Bucci R, et al. Current applications and future prospects of 3D printing in orthodontics. J Clin Orthod. 2020; 54(5):299-305.

9. Joda T, Cacace J, Ferrari M. The future of digital dentistry: 3D printing in dental applications. Dent J. 2017; 5(1):5.

10. Yap AUJ, Zainal F, Liew M, et al. Digital technologies in orthodontics: an overview of applications in clinical practice. J Dent Sci. 2019; 14(4):361-368.

11. Gan J, Wang W, Liu C, et al. 3D-printed orthodontic appliances: manufacturing and clinical considerations. J Dent. 2019; 87:44-50.

12. Malki A, O'Brien M. Use of 3D printing for clear aligner fabrication. Orthodontic Practice. 2021; 12(3):34-38.

13. Ceresoli C, Gallo M, Salvi E, et al. 3D printing in orthodontics: how technology is shaping the future. J Appl Biomater Funct Mater. 2020; 18:1-8.

14. Saman M, Kumar S, Singh S. 3D printing in orthodontics: A review. Int J Appl Dent Sci. 2021; 7(2):150-157.

15. Lubkowska A, Biernat K. 3D printing technologies in the orthodontic office: a new era in dental care. J Orthod. 2022; 47(2):118-124.

16. Rowe N, McKinney G, Wright R. Innovations in digital technologies and their impact on orthodontic practice. Clin Orthod. 2019; 53(2):93-101.

17. Buser D, Zitzmann NU, Sailer I, et al. Digital prosthodontics and 3D printing. Int J Prosthodont. 2020; 33(1):65-71.

18. Lippman S, McBride S, Wang Y. Innovations in CAD/CAM orthodontics: advancements and future trends. Orthod Pract. 2021; 12(1):7-12.

19. Tuncer M, Ozkurt S, Aksakalli S. Digital advancements in orthodontics. World J Orthod. 2021; 22(3):226-234.

20. Kolokitha O, Nikoloudakis P, Daskalogiannaki M. A systematic review of 3D printing and its role in dental and orthodontic treatments. BMC Oral Health. 2021; 21:230.

21. Zhang Y, Bai Z, Li J, et al. Application of 3D printing in orthodontics. Prog Biomater. 2018; 7(1):29-42.

22. Bernhardt L, Schott T, Stoll R, et al. Use of 3D printed models in orthodontic treatment planning. Int J Orthod. 2019; 32(3):149-157.

23. Lee JW, Lim HW, Cho Y. Applications of 3D printing in orthodontic treatment. Arch Aesthetic Plast Surg. 2020; 26(4):301-308.

24. Huang Y, Zhao Z, Wang H, et al. 3D printing for dental restoration: a comprehensive review. J Prosthet Dent. 2020; 124(4):424-430.

25. Lim YJ, Kim YH, Jang IS, et al. 3D-printed orthodontic appliances for personalized treatment: A review of current materials. J Esthet Restor Dent. 2020; 32(6):521-530.

26. Rachmiel A, Bichacho N, Kaspi D, et al. CAD/CAM technology in orthodontics: A review of recent developments. J Clin Orthod. 2021; 55(3):129-135.

27. He Y, Liu M, Zhang F, et al. Recent advances in 3D-printed orthodontic appliances. J Biomech. 2019; 97:1085-1093.

28. Liu M, Chen Z, Gao J, et al. 3D-Printed Custom Orthodontic Appliances: Advancements, Challenges, and Future Prospects. J Clin Orthod. 2023; 57(11):563-572.

29. Quintana R., Choi J.-W., Puebla K., Wicker R. Effects of build orientation on tensile strength for stereolithography-manufactured ASTM D-638 type I specimens. The International Journal of Advanced Manufacturing Technology. 2009; 46:201–215.

30. Edelmann A, English JD, Chen SJ, Kasper FK. Analysis of the thickness of 3-dimensional-printed orthodontic aligners. Am J Orthod Dentofacial Orthop. 2020; 158(5):e91-e98.

31. Ko DH, Gyak KW, Kim DP. Emerging microreaction systems based on 3D printing techniques and separation technologies. J Flow Chem. 2017; 7:72-81.

32. Solanki S, Kumar S, Singh R. The role of 3D printing in improving orthodontic procedures. World J Orthod. 2020; 21(3):295-303.

33. Chockalingam K., Jawahar N., Chandrasekhar U. Influence of layer thickness on mechanical properties in stereolithography. Rapid Prototyping Journal. 2006; 12(2):106–113.

34. Loflin WA, English JD, Borders C, Harris LM, Moon A, Holland JN, Kasper FK. Effect of print layer height on the assessment of 3D-printed models. Am J Orthod Dentofacial Orthop. 2019; 156(2):283-289.

35. Shi J, Zhang Z, Yu S. 3D printed customized orthodontic aligners: Review of current technologies. J Dent Sci. 2019; 14(4):431-436.

36. McKenna P, McNamara M. A review of recent advancements in 3D orthodontic technology. Orthod Craniofacial Res. 2020; 23(3):215-225.

37. Tang M, Li G, Zhang Z. The integration of AI with 3D printing in orthodontics. AI Open. 2021; 2(2):37-45.

38. Nascimento M, Lima A, Marques L, et al. The future of 3D printing in orthodontics: Current developments and future trends. J Dent Res. 2021; 100(10):1142-1149.

37. Li Y, Wang Z, Sun S. Precision and effectiveness of 3D printed orthodontic appliances in clinical trials. BMC Oral Health. 2020; 20(1):234.

38. Swathi S, Surya T, Muthukumar A. Applications of 3D printing in orthodontics: A review of the current literature. Int J Pharm Sci Res. 2020; 11(5):2184-2191.

39. Aranguren X, Arango J, Vega L. Overview of additive manufacturing in orthodontic care. J Dent Health. 2020; 59(5):223-228.

40. Medina E, Kumar V, Grijalva J, et al. The impact of 3D printing on orthodontic diagnostics and treatment planning. J Clin Orthod. 2018; 52(4):257-266.

41. Bernhardt L, Krumm A, Stoll R, et al. 3D printing in orthodontics: A practical guide. J Esthet Orthod. 2020; 38(2):147-152.

42. Rongo R, Sarti S, Guglielmi C. Digital workflows and the integration of 3D printing in orthodontics. Minerva Stomatol. 2020; 69(1):31-38.

43. Jiang J, Wang Y, Li J. Advances in 3D printing technologies for orthodontics: An overview. J Dent Res. 2021; 100(11):1241-1250.

44. Sassani F, Elmajian A, Roberts S. Computer-assisted fabrication of orthodontic appliances: Considering the possibilities. J Am Dent Assoc. 1995; 126(9):1296-1300.

45. Lee J, Kim T, Shin S, et al. 3D printed orthodontic appliances: Material selection and challenges. J Orthod. 2020; 47(6):458-467.

46. Cho S, Lee S, Oh S. Future implications of 3D printing in orthodontics. J Clin Orthod. 2022; 56(2):112-118.

47. Gaballah K, Khamis M, El-Hefnawy A. 3D printing in orthodontic appliances: Current trends and future perspectives. J Adv Dent Res. 2021; 10(2):67-74.

48. Tang R, Li X, Zheng W, et al. Additive manufacturing for orthodontics: New horizons in dental practice. J Prosthet Dent. 2021; 126(4):474-482.

49. Liu J, Wang Y, Wang D, et al. Advances in the use of 3D printing technology in orthodontic diagnosis and treatment. J Orthod. 2020; 47(4):236-245.

50. Ferreira S, Bavaresco L, Lucchetta F, et al. Accuracy of 3D printing in creating orthodontic models: A systematic review. J Dent. 2020; 88:103-110.

51. Sagandira CR, Siyawamwaya M, Watts P. 3D printing and continuous flow chemistry technology to advance pharmaceutical manufacturing in developing countries. Arabian J Chem. 2020; 13(11):7886-7908.

52. Rupprecht L, Schmiedel R, Kohl A, et al. 3D printing in orthodontics: An overview of the technologies and their potential. Eur J Orthod. 2021; 43(3):252-258.

53. Wang Z, Zhang L, Li Y, et al. Influence of 3D-printed orthodontic appliances on treatment outcomes: A systematic review. BMC Oral Health. 2023; 23(1):174.

54. Su W, Chen X, Yang Y, et al. 3D Printing in Orthodontic Clear Aligners: Current Applications and Future Directions. J Clin Orthod. 2023; 57(10):577-585.

55. Singh K, Bansal D, Kumar V, et al. Applications of 3D Printing in Orthodontics: A Review of Materials and Techniques. J Adv Prosthodont. 2022; 14(6):314-321.

56. Ozer T, Kocak H, Akarsu S. The Impact of 3D Printing on Orthodontic Treatment Planning and Clinical Procedures. Int J Orthod. 2022; 53(2):145-151.

57. Dinesh K, Mathen S, Shankar K. Personalized 3D-Printed Braces in Orthodontics: A Clinical Evaluation. J Orthod Sci. 2021; 10(2):89-95.

58. Patel P, Shakir M, Rizvi S. Use of 3D-Printed Surgical Guides in Orthodontic Treatment: A Review. J Oral Maxillofac Surg. 2023; 81(3):1355-1361.

59. Huda N, Shahid M, Khan Z, et al. A Review of the Role of 3D Printing in Orthodontic Diagnostics and Treatment. J Clin Periodontol. 2022; 49(7):601-610.

60. Hasan F, Saleh H, Akram K, et al. The Role of 3D Printing in Orthodontic Aligners: A Comprehensive Review. J Prosthodont. 2022; 31(5):389-396.

61. Lee S, Chen J, Chan C, et al. Future Directions of 3D-Printed Brackets and Wires in Orthodontics. J Biomech. 2023; 79:165-172.

62. Wang J, Zhang Y, Zhao C, et al. Comparative Study on the Mechanical Properties of 3D-Printed Orthodontic Brackets and Traditional Metal Brackets. Dent Mater. 2024; 40(3):367-375.

63. Kim Y, Lee S, Jung Y, et al. Accuracy of 3D-Printed Models for Orthodontic Diagnosis and Treatment Planning. J Clin Orthod. 2024; 58(6):302-308.

64. Zhang X, Li Y, Wu Q, et al. Accuracy of 3D-Printed Models. J Dent Res. 2024; 103(5):677-683.

65. Plattner A, Burgess R, Lee K, et al. 3D-Printed Trays vs. Traditional Trays: A Comparative Study. Orthod Craniofacial Res. 2023; 26(4):211-218.

66. Chaudhary S, Prasad P, Sharma A, et al. Precision of 3D-Printed Trays in Orthodontics. J Orthod Sci. 2022; 11(3):89-93.

67. Xue Z, Liu L, Sun D, et al. CAD-CAM in Guided Bonding Tools for Precise Bracket Transfer Using 3D-Printed Trays. Int J Prosthodont Restor Dent. 2023; 9(1):15-22.

68. Bachour Z, Seddik A, Kassem A, et al. Linear vs. Angular Measurement Accuracy in 3D-Printed Trays. J Clin Orthod. 2022; 56(8):453-459.

69. Sassani F, Elmajian A, Roberts S, et al. Removable Acrylic Orthodontic Appliances: A CAD-CAM Approach. J Am Dent Assoc. 2021; 152(9):669-674.

70. Al Moradi S, Shirazi H, Shekarchizadeh M, et al. Use of 3D Printing in Sleep Apnea Devices and Activators. Sleep Breath. 2024; 28(1):73-80.

71. Lekurwale S, Karanwad T, Banerjee S. Selective Laser Sintering (SLS) of 3D Printlets using a 3D Printer comprised of IR/red-diode Laser. Ann 3D Printed Med. 2022; 6(6):100054

72. Bocklet M, Ahmadi F, Tremont T, Ross L, Yao H, Andrade Jr I. Comparison of 3D-printed and laboratory-fabricated Hyrax on stress distribution and displacement of the maxillary complex: a 3D finite element study. Prog Orthod. 2024; 25:11.

73. Wheeler TT, Garvan CS, Waldman A, Ford J. Clinical efficiency of Light Force 3D-printed custom brackets in diverse practice settings. J Clin Orthod. 2024; 58(5):273-82.

74. Wang Y, Chen X, Liu X, et al. Personalized Orthodontic Treatment with 3D-Printed Clear Aligners: A Comprehensive Review. Prog Biomater. 2023; 12(4):231-240.

75. Taddei F, Sorrentino R, Ferracane JL. Advances in 3D Printing for the Fabrication of Custom Orthodontic Appliances. J Dent Res. 2023; 102(2):112-118.

76. Zhuang L, Chen S, Xie H, et al. The Use of 3D Printing in Creating Custom Braces for Orthodontics. Int J Orthod. 2023; 53(3):212-219.

77. Lee J, Kim Y, Choi S, et al. Evaluation of the Mechanical Properties of 3D-Printed Orthodontic Brackets and their Performance in Clinical Settings. J Orthod Sci. 2023; 12(1):45-52.

78. Yao Y, Zhang X, Liu S, et al. Role of 3D Printing in Producing Orthodontic Palatal Expanders: Material and Design Considerations. J Biomech. 2024; 81(2):89-96.

79. Zhang L, Zhang T, Zheng Y, et al. The Use of Stereolithography in Manufacturing Personalized 3D-Printed Orthodontic Brackets. Dent Mater. 2024; 40(2):220-227.

80. Pender N, Schmidt M, Grieve A, et al. A Clinical Comparison of 3D-Printed and Traditional Orthodontic Retainers. Am J Orthod Dentofacial Orthop. 2024; 165(3):428-434.

81. Feldman M, Anderson S, Thomas R. The impact of 3D printing on the development of orthodontic retainers: A review of current materials and methods. J Clin Orthod. 2024; 58(12):654-63.