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3D Printing in Aligners Staging Orthodontics: A Review

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Abstract: Clear aligner therapy (CAT) has become a cornerstone of modern orthodontics, offering aesthetic, comfortable, and efficient alternatives to conventional braces. Accurate staging of tooth movements is essential for treatment success, yet traditional manual workflows are prone to errors, inconsistencies, and prolonged treatment duration. The advent of 3D printing, coupled with AI-assisted digital workflows, has transformed aligner fabrication by enabling both indirect model-based and direct aligner printing with biocompatible photopolymer resins. These technologies improve precision, reproducibility, and patient-specific customization while reducing production time and material waste. Treatment planning software with machine learning optimizes force application and predicts tooth movements, enhancing clinical outcomes. Factors such as printer type, resin properties, layer thickness, and algorithm sophistication critically influence staging accuracy. Overall, the integration of 3D printing, advanced materials, and digital planning establishes a new paradigm in orthodontics, enabling faster, more accurate, and patient-centered aligner therapy with potential for teleorthodontic monitoring and same-day production.
Keywords: Clear aligner therapy; 3D printing; Digital workflow; Aligner staging; Orthodontic materials

I. INTRODUCTION

Clear aligner therapy (CAT) has rapidly emerged as a leading trend in modern orthodontics, revolutionizing both clinical practice and patient experience. A critical factor in the success of aligner therapy is accurate staging of tooth movements.[1] Each aligner is designed to produce a small, controlled displacement typically 0.15–0.25 mm per stage ensuring safe biomechanical forces and predictable treatment progression. Inaccurate staging can compromise tracking, generate unintended forces, and prolong treatment duration. Therefore, precise digital modeling and biomechanical calibration are essential to maintain fidelity between virtual treatment plans and clinical outcomes.[2] Conventional manual fabrication methods, which relied on wax setups and physical impressions, posed several limitations. Additionally, these techniques were time-consuming and lacked reproducibility, particularly in complex cases.[3] The advent of 3D printing technologies, particularly stereolithography (SLA) and digital light processing (DLP), has transformed aligner fabrication and staging. These innovations provide enhanced precision, reduced production time, improved customization, and digital storage capabilities, offering a more efficient and sustainable alternative to traditional methods. Integration of 3D printing with AI-driven staging algorithms further enables orthodontists to design adaptive treatment plans, simulate occlusal outcomes, and monitor tooth movement in real time.[4] Advances in materials science, including light-cured resins with high elasticity, durability, and transparency, ensure that printed aligners maintain structural stability and biocompatibility throughout the treatment stages.[5]

II. REVIEW OF LITERATURE

Studies have demonstrated that 3D-printed aligners provide superior dimensional accuracy and fit compared to conventional methods, contributing to more predictable tooth movements and enhanced patient comfort (Dubey et al., 2025; Shahana et al., 2025).[6,7] The development of advanced resin materials, such as UDMA-based formulations with shape memory properties, allows for consistent force application and precise biomechanical control, further optimizing clinical outcomes (Retrouvey, 2025).[8] Direct-printed aligners also reduce fabrication time and material waste, offering sustainable and efficient alternatives to traditional workflows. However, despite these advancements, challenges remain, including concerns regarding material biocompatibility, surface roughness, and long-term mechanical stability. Studies on the accuracy of 3D printed orthodontic aligners report promising clinical outcomes, with tooth movement accuracies ranging between approximately 64% and 72% for different movement types such as torque, tipping, and rotation, and near 99.6% for transverse dimensions. These results suggest that direct-printed aligners can achieve clinical efficacy comparable to traditional thermoformed aligners, particularly in mildly crowded cases.[9]

The lack of standardized testing protocols and limited clinical trials underscores the need for further research to validate the safety, durability, and efficacy of 3D-printed aligners in routine practice (Jungbauer et al., 2024; Shahana et al., 2025).[10]

A. 3D Printing Technologies in Orthodontics

Stereolithography (SLA) utilizes a UV laser to cure photopolymer resin layer by layer, providing high resolution, smooth surface finishes, and excellent precision, making it the gold standard for producing dental models, surgical guides, and aligners, though it requires post-processing and has higher material costs.[11] Digital Light Processing (DLP) cures entire layers simultaneously using a projector, delivering faster print times and fine accuracy, which suits high-volume production of orthodontic appliances and aligner models, balancing speed and detail at moderate cost. Fused Deposition Modeling (FDM) builds objects by extruding thermoplastic filaments, offering an affordable and accessible option but with lower precision, rougher surface finishes, and limited material choices, restricting its use primarily to educational models or low-cost prototypes rather than clinical-grade aligners.[12] PolyJet/MultiJet printing jets photopolymer layers and cures them instantly, enabling multi-material, variable property, and color printing with fine detail and dimensional accuracy; while this technology allows highly intricate models and customized appliances, its high cost and maintenance requirements generally limit clinical use to specialized cases.[13,14]

B. Materials for 3D-Printed Orthodontic Models and Aligners

Modern orthodontic workflows increasingly rely on biocompatible photopolymer resins for 3D-printed models and thermoplastic polymers for aligners, with research now advancing toward directly 3D-printed aligners to enhance precision, efficiency, and sustainability. Dental models, typically fabricated using SLA or DLP resins, must maintain dimensional accuracy, mechanical strength, and stability under thermoforming stress, even though they are not worn intraorally.[15] Commonly used materials include Standard Grey Resin, Dental Model Resin, and Draft Resin, while medical-grade formulations such as Dental SG, Dental LT Clear, and KeyModel Ultra comply with ISO 10993-1 standards for cytotoxicity, genotoxicity, and hypersensitivity. Proper post-curing and washing are critical, as incomplete polymerization can release residual monomers and increase cytotoxicity; studies show that optimized UV curing and ethanol washing enhance both mechanical stability and biocompatibility. Thermoplastic aligners, conventionally vacuum- or thermoformed over printed models, require clarity, elasticity, and deformation resistance under masticatory forces.[16] Common materials include polyurethane (PU) for flexibility and durability, polyethylene terephthalate glycol (PETG) for optical stability, polycarbonate (PC) and polypropylene (PP) for mechanical strength, and multilayer hybrid polymers such as Zendura FLX, Duran+, and SmartTrack designed for progressive force delivery and crack resistance. In vitro studies indicate that thermoplastics generally leach fewer monomers than light-cured resins, supporting safer long-term intraoral use. Emerging research on directly 3D-printed aligners uses photopolymer resins such as Tera Harz TC-85, offering mechanical strength, transparency, and ISO 10993-compliant biocompatibility while eliminating the thermoforming step.[17] Direct printing improves accuracy by avoiding vacuum-form distortion, enables rapid same-day production, and supports highly customized staging.[18]

C. Digital Workflow in Clear Aligner Staging

The digital workflow has fundamentally transformed clear aligner therapy by integrating precise data acquisition, advanced treatment planning, and efficient fabrication, significantly improving speed, customization, and accuracy compared to conventional methods. High-resolution intraoral scanning, often complemented by CBCT imaging, replaces traditional impressions, providing detailed 3D representations of the dentition and surrounding anatomical structures for enhanced patient comfort and diagnostic precision. Specialized treatment planning software digitally segments individual teeth and simulates incremental tooth movements, generating stepwise aligner sequences.[19] Many programs leverage AI and machine learning to optimize force application, predict treatment outcomes, and customize staging while anticipating potential refinements. Sequential digital models are then produced via 3D printing, either for traditional vacuum-formed aligners or for direct fabrication of aligners using flexible photopolymer resins.[20] Direct printing reduces intermediate steps, supports same-day production, and enhances material consistency.[21] Furthermore, cloud-based platforms facilitate collaboration among clinicians, laboratories, and patients, allowing remote monitoring, early intervention, and real-time treatment adjustments.[22]

D. Factors Affecting Staging Accuracy in Clear Aligner Therapy

The precision of clear aligner staging is influenced by multiple interrelated factors, including printer type, material properties, layer thickness, and digital planning algorithms. Different 3D printing technologies yield varying levels of accuracy; for instance, DLP printers with optimal layer heights around 50 µm have been shown to produce highly precise dental models, whereas SLA printers achieve improved fidelity with slightly increased layer heights.[23] The mechanical and biocompatible characteristics of printing resins are equally critical; materials such as Tera Harz TC-85DAC demonstrate reliable clinical performance, but accurate curing protocols are essential to minimize dimensional errors. Layer thickness also plays a pivotal role, as finer layers enhance surface resolution but may increase cumulative deviations and print times, necessitating an optimal balance to maintain both precision and efficiency. In addition, the sophistication of treatment planning software including AI-assisted staging and force simulation directly impacts the predictability of tooth movements and overall treatment outcomes.[24] High staging accuracy translates into improved treatment efficiency by reducing the need for refinements, shortening overall treatment duration, and enhancing patient comfort through well-fitted aligners that deliver controlled forces. Furthermore, in-office 3D printing enables rapid model or aligner production, accelerating treatment initiation and adjustments, streamlining clinical workflow, and improving patient satisfaction.[25]

III. CONCLUSION

3D printing has revolutionized aligner staging by enhancing precision, efficiency, and patient-specific customization. Direct printing of clear aligners eliminates the need for thermoforming, streamlining production and improving material consistency. ombined with biocompatible materials and teleorthodontic integration, these advancements support more effective, patient-centered orthodontic care.

REFERENCES

[1] Konda P, Rafiq AM. 3D printing: Changing the landscape of orthodontics [Internet]. **IP Indian J Orthod Dentofacial Res**. 2024 [cited 2025 Oct 16];10(3):149-157. Available from: https://doi.org/10.18231/j.ijodr.2024.029

[2] AlMogbel A. Clear Aligner Therapy: Up to date review article. J Orthod Sci. 2023 Sep 4;12:37. doi: 10.4103/jos.jos_30_23. PMID: 37881665; PMCID: PMC10597356.

[3] Abreu LG, Drumond VZ, Mesquita RA, Bernabé E, Almeida de Arruda JA. Optimising clear aligner therapy: What current evidence says about materials, attachments, and protocols. Semin Orthod. [Internet]. 2025 Jul 29 [cited 2025 Oct 16]

[4] https://sprintray.com/learn-3d-printing-clear-aligner-workflow-cloud-design/

[5] Alkhamees A. The new additive era of orthodontics: 3D-printed aligners and shape memory polymers-the latest trend-and their environmental implications. J Orthod Sci. 2024 Nov 25;13:55. doi: 10.4103/jos.jos_211_23. PMID: 39758107; PMCID: PMC11698253.

[6] Dubey, S., Dash, B. P., Mohanty, B., Jena, S., Sahoo, N., & Singh, S. (2025). 3D printing in orthodontics - Past, present and future: A systematic review and meta-analysis. <i>Bioinformation</i>. https://doi.org/10.6026/973206300211766</div>

[7] Shahana, S., Kumar, J., Mearish, P., & Manas, G. (2025). Direct printed aligners: a paradigm shift in digital orthodontics. International Journal of Scientific Research, 26–28. https://doi.org/10.36106/ijsr/9106920

[8] Retrouvey, J.-M. (2025). Assessment of active memory of photo-curable resins for LuxCreo DCA direct-printed 3D aligners. APOS Trends in Orthodontics, 0, 1–6. https://doi.org/10.25259/apos_61_2025

[9] Jungbauer, R., Sabbagh, H., Janjić Ranković, M., & Becker, K. (2024). 3D Printed Orthodontic Aligners—A Scoping Review. Applied Sciences, 14(22), 10084. https://doi.org/10.3390/app142210084

[10] Narongdej, P., Hassanpour, M., Alterman, N., Rawlins-Buchanan, F., & Barjasteh, E. (2024). Advancements in Clear Aligner Fabrication: A Comprehensive Review of Direct-3D Printing Technologies. Polymers, 16. https://doi.org/10.3390/polym16030371

[11] Camenisch, L., Polychronis, G., Panayi, N. C., Makou, O., Papageorgiou, S. N., Zinelis, S., & Eliades, T. (2024). Effect of printing orientation on mechanical properties of 3D-printed orthodontic aligners. Journal of Orofacial Orthopedics-Fortschritte Der Kieferorthopadie. https://doi.org/10.1007/s00056-023-00511-0

[12] Jun, M.-K., Kim, J. W., & Ku, H. (2025). 3D Printing in Dentistry: A Scoping Review of Clinical Applications, Advantages, and Current Limitations. https://doi.org/10.20944/preprints202502.1346.v1

[13] Li, H. (2023). 3D printing in orthodontics: A narrative review. Journal of International Oral Health: JIOH, 15(1), 15. https://doi.org/10.4103/jioh.jioh_83_22

[14] Avolese, S., Parrini, S., Lugas, A. T., Bignardi, C., Terzini, M., Guajardo Cantu, V., Castroflorio, T., Grifalconi, E., Scotti, N., & Sanna, F. (2025). A Comparison Between the Expansion Force Exerted by Thermo-Printed Aligners and 3D Printed Aligners: An In Vitro Study. Bioengineering, 12(9), 912. https://doi.org/10.3390/bioengineering12090912

[15] Zinelis S, Panayi N, Polychronis G, Papageorgiou SN, Eliades T. Comparative analysis of mechanical properties of orthodontic aligners produced by different contemporary 3D printers. Orthod Craniofac Res. 2022 Aug;25(3):336-341. doi: 10.1111/ocr.12537. Epub 2021 Oct 4. PMID: 34569692; PMCID: PMC9544566.

[16] Kumar GS, Dharshini CP, Soman PS, Abraham A. 3D printing – A paradigm shift in orthodontic appliances and patient care [Internet]. **J Dent Panacea**. 2024 [cited 2025 Oct 16];6(4):171-180. Available from: https://doi.org/10.18231/j.jdp.2024.035

[17] Gökmen Ş, Görgülü S, Topsakal KG, Duran GS. Accuracy of 3D Printer Technologies Using Digital Dental Models. Turk J Orthod. 2024 Dec 31;37(4):257-264. doi: 10.4274/TurkJOrthod.2024.2023.8.

[18] Ergül T, Güleç A, Göymen M. The Use of 3D Printers in Orthodontics - A Narrative Review. Turk J Orthod. 2023 Jun 22;36(2):134-142. doi: 10.4274/TurkJOrthod.2022.2021.0074. PMID: 37346463; PMCID: PMC10318848.

[19] Prakash J, Shenoy M, Alhasmi A, Al Saleh AA, C SG, Shivakumar S. Biocompatibility of 3D-Printed Dental Resins: A Systematic Review. Cureus. 2024 Jan 5;16(1):e51721. doi: 10.7759/cureus.51721. PMID: 38318586; PMCID: PMC10839546.

[20] Guttridge C, Shannon A, O'Sullivan A, O'Sullivan KJ, O'Sullivan LW. Biocompatible 3D printing resins for medical applications: A review of marketed intended use, biocompatibility certification, and post-processing guidance. Ann 3D Print Med. 2022 Mar;5:100044.

[21] Guerrero-Gironés J, López-García S, Pecci-Lloret MR, Pecci-Lloret MP, Rodríguez Lozano FJ, García-Bernal D. In vitro biocompatibility testing of 3D printing and conventional resins for occlusal devices. J Dent. 2022 Aug;123:104163.
[22] Francisco I, Paula AB, Ribeiro M, Marques F, Travassos R, Nunes C, Pereira F, Marto CM, Carrilho E, Vale F. The Biological Effects of 3D Resins Used in Orthodontics: A Systematic Review. Bioengineering (Basel). 2022 Jan 3;9(1):15. doi: 10.3390/bioengineering9010015. PMID: 35049724; PMCID: PMC8773237.
[23] Meade MJ, Ng E, Weir T. Digital treatment planning and clear aligner therapy: A retrospective cohort study. J Orthod. 2023 Dec;50(4):361-366. doi: 10.1177/14653125231166015. Epub 2023 Apr 1. PMID: 37002790; PMCID: PMC10693725.
[24] Migliorati M, Drago S, Castroflorio T, Pesce P, Battista G, Campobasso A, Gastaldi G, Valvecchi FF, Mari A. Accuracy of orthodontic movements with 3D printed aligners: A prospective observational pilot study. Korean J Orthod. 2024 May 25;54(3):160-170. doi: 10.4041/kjod23.268. Epub 2024 Apr 8. PMID: 38800861; PMCID: PMC11129935.
[25] Torkomian T, de la Iglesia F, Puigdollers A. 3D-printed clear aligners: An emerging alternative to the conventional thermoformed aligners? – A systematic review. J Dent. 2025 Apr;155:105616.