International Journal of Applied Dental Sciences 2025; 11(4): 666-669

ISSN Print: 2394-7489
ISSN Online: 2394-7497
Impact Factor (RJIF): 7.85
IJADS 2025; 11(4): 666-669

www.oraljournal.com
Received: 09-09-2025
Accepted: 13-10-2025

Christian Arias
Centro Universitario do Norte Paulista. São Paulo, Brazil

Katty Rios
Universidad Científica del Sur. Lima, Peru

Corresponding Author:
Christian Arias
Centro Universitario do Norte Paulista. São Paulo, Brazil

Digitally aligned orthodontics: Advances in 3d printing and clear aligners

Christian Arias and Katty Rios

DOI: https://www.doi.org/10.22271/oral.2025.v11.i4g.2310

Abstract
Introduction: Digitally aligned orthodontics has evolved significantly with the incorporation of digital workflows and 3D printing technologies, enabling for more accurate planning and more controlled manufacturing of clear aligners.
Objective: To analyze recent scientific evidence on technological advances, the accuracy of digital *setups* and the application of 3D printing in the manufacture of transparent aligners in orthodontics.
Methodology: A search for literature articles published in the last five years in PubMed, Scopus, ScienceDirect and Google Scholar was conducted. Terms such as "Clear Aligners", "Digital Orthodontics", "3D Printing" and "Virtual Setup" were used. We included *in vitro* experimental studies, comparative studies, and clinical studies that evaluated tooth movement accuracy, mechanical properties of materials, and digital workflows.
Results: Evidence indicates that directly 3D printed aligners exhibit greater geometric accuracy and better thickness control than thermoformed aligners, with three-dimensional deviations below 0.2 mm *in vitro* studies. Digital planning allows staged movements of 0.2-0.3 mm and rotations of 1-3°, although predictability is lower for complex movements, such as rotations and extrusions.
Conclusion: Digitally aligned orthodontics supported by 3D printing is an effective and promising tool; however, its clinical success depends on rigorous planning, proper material selection, and mastery of digital flow.

Keywords: Digital orthodontics, Clear aligners, 3D printing, Virtual planning

Introduction

Orthodontics has undergone a significant evolution with the incorporation of digital technologies that have improved planning, clinical accuracy and treatments predictability [1]. The growing demand for aesthetic, functional and personalized orthodontic therapies has driven the development of systems based on fully digital workflows, highlighting the use of transparent aligners designed through virtual planning and manufactured with 3D printing technologies [2–4]. In this context, the so-called *Digitally aligned orthodontics* integrates intraoral scanning, virtual *setup* technology, tooth movements simulations and computer-assisted manufacturing, becoming a cornerstone of modern orthodontics [5, 6].

3D printing has particularly transformed aligners manufacturing, enabling both indirect production through printed models and thermoforming as well as the direct printing of aligners using photopolymerizable resins specifically for orthodontic use [7, 8]. Grant *et al.* [9], Knode *et al.* [10] and Mendonça *et al.* [11] have shown that 3D printed aligners offer greater control over the thickness, extension, and mechanical properties of the material, reducing the dimensional variations inherent to conventional thermoforming and improving clinical fit accuracy. In addition, the elimination of intermediate steps in the manufacturing process contributes to greater efficiency of the digital flow and a reduction in production time [12, 13]. However, one of the main challenges reported in the literature is the discrepancy between the planned digital *setup* and actual tooth movement achieved during aligner treatment. Although virtual planning systems allow simulation of sequential three-dimensional movements, limitations in the predictability of certain movements, such as rotations, extrusions and root inclinations, have been described that may require additional refinements [1, 14–16]. These results show that clinical accuracy is influenced by multiple factors, including the type of material, the design of the material and the *attachments*, the aligner thickness and the applied biomechanics [11, 17].

At the same time, the integration of artificial intelligence (AI) in orthodontic planning has opened new perspectives to optimize diagnosis, improve the prediction of tooth movements and automate treatment monitoring. However, despite its potential, the available clinical evidence remains heterogeneous and limited, requiring a critical evaluation of its applicability in daily practice [4, 18, 19]. Likewise, the development of *in-office* workflows has enable comparison between in-clinic printed aligners and commercial systems, revealing advantages in process control and cost reduction, but also challenges related to standardization, materials biocompatibility and regulatory aspects [7, 20, 21].

In this scenario of rapid technological advancement and diverse approaches, the need for a critical and updated review that integrates the available scientific evidence on digitally aligned orthodontics becomes evident. The objective of this review is to synthesize advances in 3D printing and transparent aligners, analyze the accuracy of digital *setup*, evaluate the incorporation of artificial intelligence and compare commercial aligners versus clinically printed aligners, providing a comprehensive view of their real impact on contemporary orthodontic practice.

Material and Methods

A review of the scientific literature published in the academic databases PubMed, ScienceDirect, Scopus, and Google Scholar was conducted, covering articles published within the last three years. The selection of studies followed the standard stages for scientific reviews, including identification, evaluation, selection, and inclusion of articles relevant to the review's objective. Priority was given to clinical studies, *in vitro* studies, systematic reviews, and narrative reviews addressing digital orthodontics, 3D printing, and the use of transparent aligners. The methodological quality of the selected articles was assessed based on study design, methodological clarity, clinical relevance and relevance of the results, with special emphasis on research related to the manufacture of aligners using 3D printing, the accuracy of digital *setups*, prediction tooth movement, and the integration of digital technologies and artificial intelligence in orthodontic planning.

The search strategy was structured by using Boolean operators (AND, OR, NOT) to combine the key terms. Keywords used in English included: *"Clear Aligners", "Digital Orthodontics", "3D Printing", "Direct-Printed Aligners", "Virtual Setup", "Tooth Movement Accuracy*", *"Orthodontic Biomechanics*", *"Artificial Intelligence"* and *"In-office Aligner Manufacturing".*

Results

Precision of digital *setup* and accuracy of tooth movement

Several studies have evaluated the correspondence between the planned digital *setup* and actual tooth movement achieved during treatment with clear aligners. Jungbauer *et al.* [1] analyzed the clinical predictability of planned movements using aligners and noted a discrepancy between virtual and clinical movement, identifying rotations and extrusions as the movements at the least predictability. Similarly, Konda *et al.* [15] assessed the performance of three-dimensional digital planning and concluded that the accuracy of tooth movement depends on the type of movement and the biomechanical design incorporated in the aligner.

Krymovskyy *et al.* [14] evaluated the accuracy of tooth movement through digital model superimposition and reported that inclination and torque movements show greater deviations compared to simple linear movements. Narongdej *et al.* [16] provided relevant quantitative data on the biomechanical parameters used in aligner planning. Their results indicated that the planned tooth movements per stage typically range from 0.2 to 0.3 mm for translations and 1 to 3° for rotations, applied at approximately 14-day intervals. They also described orthodontic force ranges associated with diverse types of movement, with approximate values of 0.5-0.75 N for tipping, 1-1.5 N for rotation, and 0.75-1.25 N for torque and body movements, noting that deviations in these parameters may increase the need for additional refinements.

Finally, Niu *et al.* [17] evaluated the mechanical behavior of directly printed aligners and reported that the material properties and aligner thickness directly influence the magnitude and distribution of the forces exerted on the teeth.

3D printing technologies and materials for clear aligners

Recent literature has consistently documented the impact of 3D printing on the manufacture of clear aligners. Rajasekaran *et al.* [7] described the integrated manufacturing workflow for directly 3D printed aligners, highlighting improved control over thickness aligner, extension, and adaptation compared to conventional thermoformed methods. Erbe *et al.* [8] evaluated the biocompatibility and mechanical behavior of light-curing resins for directly printed aligners, reporting clinically acceptable results, although further research is needed on the release of monomers and the aging of the material.

Grant *et al.* [9] analyzed the forces and moments generated by 3D printed aligners and reported a more homogeneous force distribution compared to thermoformed aligners. Mendonça *et al.* [11] observed that the mechanical properties of the material, particularly the elastic modulus and shape memory, directly influence the efficiency of tooth movement. Knode *et al.* [10] and Alkhamees *et al.* [13] agreed that direct printing reduces thermoforming-induced dimensional variations, improving the reproducibility of the aligner.

Influence of print parameters on dimensional accuracy

Several studies have evaluated the influence of 3D printing parameters on the dimensional accuracy of models and aligners. Tongkitcharoen *et al.* [20] analyzed the effect of the type of base (hollow or solid) and printing orientation, reporting that models printed in horizontal orientation with a solid base exhibited the highest accuracy, while the vertical orientation showed greater deviations, especially in the rear sector. Nagib *et al.* [21] assessed the accuracy of *attachments* manufactured using 3D printing and noted that the scan quality and print resolution directly influence the stability and clinical adaptation of orthodontic accessories. Sreejith *et al.* [4] highlighted that the choice of printing technology (SLA, DLP or LCD) and post-curing protocol affects both the dimensional accuracy and the final mechanical properties of the printed product. Accordingly, Almarshadi *et al.* [3] and Harikrishnan *et al.* [6] reported that standardization of printing parameters is essential to ensure reproducible clinical results.

Integrating Artificial Intelligence into Aligner Planning

The incorporation of artificial intelligence in orthodontic planning has been addressed in several recent studies. Dubey *et al.* [18], in their systematic review, noted that AI-based systems allow improving tooth segmentation, movement simulation and outcome prediction, although clinical evidence is still limited. Alhazmi *et al.* [19] described AI applications in automated digital model analysis, highlighting a reduction in planning time and greater consistency in the design of the *setup*. Bichu *et al.* [12] evaluated the impact of automation on aligner biomechanics and observed that AI-assisted planning can optimize the sequence of movements, although it does not completely eliminate the need for clinical adjustments. Ahmed *et al.* [2] and Dua *et al.* [5] agreed that AI represents a complementary, but not a substitute, tool for the orthodontist's clinical judgment.

Comparison between commercial aligners and clinically printed aligners

The comparison between commercial aligners and clinically printed aligners has been the subject of multiple investigations. Rajasekaran *et al.* [7] showed that printed aligners *in-office* can achieve accuracy levels comparable to commercial systems, particularly in simple linear motions. Tongkitcharoen *et al.* [20] noted that the final accuracy is highly dependent on the control of the digital flow and the printing parameters used.

Narongdej *et al.* [16] and Mendonça *et al.* [11] reported that clinically printed aligners offer advantages in terms of cost reduction and production times, although they require greater technical expertise and quality control. Niu *et al.* [17] and Knode *et al.* [10] emphasized that materials standardization and essential protocols for *in-office* aligners to achieve consistent clinical outcomes comparable to commercial systems.

Clinical implications and observed benefits

Among the main clinical advantages observed are greater treatment customization, reduced aligner production time, and better control of the biomechanical design. Sreejith *et al.* [4] and Harikrishnan *et al.* [6] highlighted that comprehensive digital workflows improve patient communication and facilitate interdisciplinary planning. Jungbauer *et al.* [1] and Krymovskyy *et al.* [14] noted that, despite predictability limitations in certain movements, digitally aligned orthodontics enables a more controlled and systematic approach to treatment.

The studies analyzed confirm that the combination of digital planning, 3D printing, and emerging technologies such as artificial intelligence represents a significant advance in contemporary orthodontics, although challenges remain related to clinical accuracy, protocols standardization, and long-term validation of the materials used.

Table 1: High-quality experimental evidence on digitally aligned orthodontics and 3D printing of clear aligners.

I am a student	Study design	Sample/material evaluated	Intervention	Key findings
Erbe et al. (2022) [8]	Experimental laboratory study	Light-curing resins for directly printed aligners	Evaluation of mechanical behavior and biocompatibility	The resins evaluated showed mechanical properties and biocompatibility acceptable for intraoral use. The post-curing protocol significantly influenced the mechanical behavior.
Narongdej et al. (2022) [16]	In vitro *experimental study*	Aligners printed directly in 3D with different thicknesses and materials	Mechanical characterization and analysis of orthodontic forces and moments	The directly printed aligners generated orthodontic forces within clinically acceptable ranges. The planned movement per stage was 0.2–0.3 mm for translations and 1–3° for rotations, with force magnitudes between 0.5 and 1.5 N depending on the type of movement. Material and thickness significantly influenced the predictability of movement.
Dubey et al. (2023) [18]	In vitro controlled comparative study	3D printed aligners vs. thermoformed aligners (Zendura FLX™, Essix ACE)™	*Trueness* and accuracy evaluation using three-dimensional deviation analysis	The 3D printed aligners presented lower RMS deviation (0.140 ± 0.020 mm) compared to thermoformed aligners (0.188 ± 0.074 mm and 0.209 ± 0.094 mm), demonstrating greater geometric accuracy and reproducibility of the direct printing process.
Niu et al. (2023) [17]	In vitro comparative study of materials	Materials for printed aligners (Dental LT, TC-85A and other photopolymers)	Evaluation of mechanical and viscoelastic properties	The TC-85A material showed favorable viscoelastic behavior and shape memory effect, while Dental LT showed adequate mechanical resistance with different relaxation pattern. The differences between materials directly influenced the stability of the applied force and the precision of tooth movement.
Rajasekaran et al. (2024) [7]	Comparative experimental study	In-office printed aligners vs. commercial systems	Evaluating Digital Flow Accuracy and Efficiency	The clinic-printed aligners achieved accuracy comparable to commercial systems in simple movements. Reduced production time and greater control of digital flow were observed, although accuracy depended on strict control of printing parameters and biomechanical design.

Conclusions

Digitally aligned orthodontics, based on virtual planning and the use of 3D printing technologies for manufacturing clear aligners, has demonstrated significant technical advantages over conventional approaches. The evidence reviewed indicates that directly 3D printed aligners provide greater control of the design, thickness and mechanical properties of the device, resulting in improved geometric accuracy and more consistent force delivery. Likewise, digital *setup* systems enable three-dimensional simulation of tooth movement and optimize treatment planning, particularly for simple linear movements.

However, the studies reviewed also highlight important limitations. The predictability of tooth movement remains variable, especially in complex movements such as rotations, extrusions and root inclinations, which often require additional refinement. Factors such as material type, aligner thickness, biomechanical design, 3D printing parameters, and individual patient biological response significantly influence the clinical accuracy obtained. Furthermore, the methodological heterogeneity among studies and the limited availability of long-term clinical evidence highlight the need to standardize manufacturing, validation, and clinical evaluation protocols.

Overall, this review confirms that the integration of digital planning, 3D printing and, at an early stage, artificial intelligence represents an effective and promising tool in contemporary orthodontics.

Conflict of Interest

Not available

Financial Support
Not available

References

1. Jungbauer R, Sabbagh H, Janjic Rankovic M, Becker K. 3D printed orthodontic aligners: a scoping review. Applied Sciences. 2024;14(22):10084.
2. Ahmed N, Shetty SK, Urukalan H, PMN, Younus A, Bhat KR. Thinking forward: 3-D printing in orthodontics. IP Indian Journal of Orthodontics and Dentofacial Research. 2025;7(3):208–215.
3. Almarshadi R, Hamdi S, Hadi F, Alshehri A, Alsahafi R, Aljohani N, et al. Redefining digital dentistry: multidisciplinary applications of 3D printing for personalized dental care. Cureus. 2025 Jun 26;17.
4. Sreejith Kumar G, Priya Dharshini C, Soni Soman P, Abraham A. 3D printing: a paradigm shift in orthodontic appliances and patient care. Journal of Dental Panacea. 2025;6(4):171–180.
5. Dua V, Sachdeva M, Arya S, Sagar B. Simplifying digital planning with clear aligners: a review. Journal of Dental Panacea. 2025;6(1):26–33.
6. Harikrishnan S, Subramanian AK. 3D printing in orthodontics: a narrative review. Journal of International Oral Health. 2023;15(1):15.
7. Rajasekaran A, Chaudhari PK. Integrated manufacturing of direct 3D-printed clear aligners. Frontiers in Dental Medicine. 2023 Jan 6;3.
8. Erbe C, Ludwig B, Bleilöb M. Unlocking the biological insights of 3D printed aligners: a look at current findings. Seminars in Orthodontics. 2025;31(1):139–143.
9. Grant J, Foley P, Bankhead B, Miranda G, Adel SM, Kim KB. Forces and moments generated by 3D direct printed clear aligners of varying labial and lingual thicknesses during lingual movement of maxillary central incisor: an in vitro study. Progress in Orthodontics. 2023;24:23.
10. Knode V, Ludwig B, Retrouvey JM, Pandis N, Schmid JQ, Erbe C, et al. Directly printed aligner therapy: a 12-month evaluation of application and effectiveness. American Journal of Orthodontics and Dentofacial Orthopedics. 2025;167(1):73–79.
11. Mendonça LMS, Queiroga KVOC, Silva EAS, Costa N, Ponte ARS, Ponte ANL, et al. Propriedades mecânicas dos alinhadores ortodônticos impressos de maneira direta em comparação com os alinhadores termoformados. Research, Society and Development. 2025 Jan 21;14(1):e7414148031.
12. Bichu YM, Alwafi A, Liu X, Andrews J, Ludwig B, Bichu AY, et al. Advances in orthodontic clear aligner materials. Bioactive Materials. 2023;22:384–403.
13. Alkhamees A. The new additive era of orthodontics: 3D-printed aligners and shape memory polymers the latest trend—and their environmental implications. Journal of Orthodontic Science. 2024;13:55.
14. Krymovskyy KG, Zhehulovych ZE, Storozhenko KV, Babaskin YI. Nowadays and the future of the 3D digital technologies in modern orthodontics. Wiadomości Lekarskie. 2024;77(10):2047–2056.
15. Konda P, Mohammed Rafiq A. 3D printing: changing the landscape of orthodontics. IP Indian Journal of Orthodontics and Dentofacial Research. 2025;10(3):149–157.
16. Narongdej P, Hassanpour M, Alterman N, Rawlins-Buchanan F, Barjasteh E. Advancements in clear aligner fabrication: a comprehensive review of direct-3D printing technologies. Polymers. 2024;16(3):371.
17. Niu C, Li D, Zhang Y, Wang Y, Ning S, Zhao G, et al. Prospects for 3D-printing of clear aligners: a narrative review. Frontiers in Materials. 2024 Jul 30;11.
18. Dubey S, Prasad Dash B, Mohanty B, Jena S, Sahoo N, Singh S. 3D printing in orthodontics: past, present and future a systematic review and meta-analysis. Bioinformation. 2025;21(6):1766–1774.
19. Alhazmi A. Advancements in orthodontic aligner fabrication: a comparative review of 3D printing technologies and traditional methods evaluation. Journal of Contemporary Dental Practice. 2025;26(6):632–637.
20. Tongkitcharoen N, Manopattanakul S, Boonpratham S, Santiwong P, Viwattanatipa N. Comparison of dimensional accuracy of 3D printing model for clear aligner among various orientation types and hollow types. Clinical Investigations in Orthodontics. 2023;82(4):177–193.
21. Nagib R, Chircu A, Szuhanek C. Integrating 3D digital technology advancements in the fabrication of orthodontic aligner attachments: an in vitro study. Journal of Clinical Medicine. 2025;14(14):5093.

How to Cite This Article
Arias C, Rios K. Digitally aligned orthodontics: Advances in 3d printing and clear aligners. International Journal of Applied Dental Sciences 2025; 11(4): 666-669.