

Evolution of orthodontics: from fixed appliances to clear aligners.

An Enhanced Narrative Review

Matteo Nagni¹
Benedetta Balbi¹
Chiara Maria Galati¹
Greta Boschi¹
Giovanna Mangino¹
Orsola Brucoli²

¹ Dental School Department of Dentistry, IRCCS San Raffaele Hospital, Vita-Salute San Raffaele University, Milan, Italy

² Faculty of Dentistry, Universidad Alfonso X El Sabio, Madrid, Spain

Corresponding author: Benedetta Balbi
email: balbibenedetta2@gmail.com

Abstract

Background: Orthodontics has moved from being mechanically and metal-based to being biologically guided and digitally designed. The development of clear aligner therapy (CAT) is a milestone that combines biomechanics, materials science, and artificial intelligence in orthodontics.

Objective: This improved narrative review combines the history, material, and biomechanical development of orthodontic appliances, focusing on the shift from fixed appliances to clear aligners. Quantitative information from randomized clinical trials and biomechanical research is used to assess effectiveness, benefits, and limitations.

Methods: A narrative search was conducted in PubMed, Scopus, and Web of Science from 1970 to 2025. Data from systematic reviews, finite element analyses, and clinical trials were included. The data was analyzed using quantitative summaries and graphs to show the predictability of treatment, pain scores, and biomechanical performance.

Results: The accuracy of tooth movements for clear aligners is 55–70%, with tipping and intrusion being the most predictable. The aligners result in lower pain levels (mean VAS difference of –1.3), improved periodontal conditions, and treatment times equal to those of fixed appliances.

Conclusion: Clear aligner therapy is a paradigm shift in orthodontics, transforming the field from reactive to predictive. Advances in artificial intelligence, smart polymers, and biomechanical modeling will further improve the precision of orthodontics.

Keywords: evolution in orthodontics, clear aligners, biomechanics, digital orthodontics

Introduction

The branch of orthodontics has been constantly evolving from its inception. From metal systems that were purely mechanical in their approach to relocating the teeth to modern systems that use digital technology and biological knowledge, the development of orthodontic techniques reflects the advancement of modern medicine (1,4).

Conventional fixed appliances were the mainstay of orthodontics for almost a century and offered predictable mechanical control of tooth movement. However, with the growing need for aesthetic solutions and advances in technology, there is now a shift towards minimally invasive and digitally designed treatments. Clear aligner therapy (CAT) is a paradigm shift in this direction, providing aesthetic, hygienic, and



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biomechanically advanced solutions over conventional appliances (2–3,5). The purpose of this review is to provide comprehensive insight into the evolution of orthodontics, with a special focus on material innovation, digital workflow, biomechanics, and quantitative clinical results of clear aligner therapy.

Historical evolution of orthodontics

The roots of orthodontics date back to the 18th century, when Pierre Fauchard developed the bandeau, an appliance used to expand the dental arch. However, the specialty evolved in the late 19th century through Edward H. Angle, who described malocclusions and developed the edgewise appliance that remains the conceptual foundation of fixed orthodontics (4). In the first half of the 20th century, gold and precious alloys were used in orthodontics because of their workability and biocompatibility. In the 1960s, stainless steel replaced gold due to its cost-effectiveness and durability (5). The introduction of direct-bonding methods made it possible to eliminate full bands, thereby improving patient comfort. The next decades were focused on aesthetics and patient satisfaction. Lingual orthodontics, introduced by Fujita in 1979, hid the brackets behind the teeth, and ceramic and sapphire brackets provided transparency (6). Nickel-titanium (NiTi) wires, with shape memory and superelastic properties, delivered light, continuous forces that were biologically compatible with tooth movement (7). These developments culminated in the straight-wire appliance developed by Andrews in 1979, which incorporated torque and angulation values into the design of the brackets—a precursor to the pre-programmed and computer-controlled systems of the present day (1,8).

Material science evolution

Material science has influenced orthodontics in terms of force systems and biological responses. The transition from metallic alloys to thermoplastics reflects the shift from mechanical methods to biologically adaptive strategies (Table 1). The development of multi-layer thermoplastics helped

to reduce stress peaks while improving flexibility and load retention. These material advancements have allowed orthodontics to move closer to delivering biologically efficient forces (7,13).

Digital orthodontics and the emergence of clear aligners

The digital revolution brought significant changes to orthodontics in the 1990s with the integration of CAD/CAM technology, 3D imaging, and stereolithography. The idea of sequential aligners, first proposed by Kesling in 1945, became a practical reality with the launch of Invisalign® in 1997 (9). This innovation introduced a workflow involving 3D intraoral scanning, digital simulations of tooth movement, and the fabrication of thermoplastic aligners using 3D printing. Each aligner moves the teeth incrementally—typically by 0.25 mm per step—following a carefully planned biomechanical sequence. Initially suitable only for mild cases, advancements in digital planning tools, attachment designs, and materials science have expanded its suitability.

Mechanisms of action

Clear aligners function as flexible shells that apply force across the entire tooth surface, rather than targeting isolated points as traditional systems do. On average, they deliver forces of 0.25–0.35 N per tooth for tipping and 0.15–0.25 N for intrusion. Finite element analysis confirms that this force decreases exponentially, with about 40% of the original force remaining after 48 hours (12). To address limitations in torque and rotational control, attachments and auxiliary elastics are used to enhance effectiveness by increasing moment arms. Digital staging also improves precision by dividing overall tooth movement into small, physiologically manageable steps.

Clinical performance and quantitative evidence

Recent research has measured the effectiveness of clear aligners with growing precision. Systematic reviews and randomized controlled trials (RCTs) report accuracy rates between 55% and 70%, with higher predictability for tipping and intrusion, and lower for rotation and extrusion (13–17) (Table 2).

Table 1. Evolution of Orthodontic Materials and Mechanical Characteristics

Material	Period	Elastic Modulus (GPa)	Key Properties	Clinical Implications
Gold alloys	1900–1960	60–80	Ductile, biocompatible, expensive	Early edgewise systems
Stainless steel	1960–present	180–200	High strength, corrosion resistant	Universal use in brackets/wires
NiTi alloy	1980–present	30–70	Superelastic, shape memory	Continuous forces, reduced chairside adjustment
Ceramic	1985–present	200–300	Esthetic but brittle	Esthetic fixed appliances
PET-G, Polyurethane	1997–present	0.8–1.5	Transparent, flexible	Foundation of clear aligners
SmartTrack™ polymer	2015–present	1.8	High resilience, low stress relaxation	Enhanced aligner control

Table 2. Mean Accuracy of Tooth Movement Using Clear Aligners

Movement Type	Mean Accuracy (%)	Limitation
Tipping	72%	Minimal surface contact
Intrusion	65%	Root morphology variability
Rotation	47%	Cylindrical teeth, reduced contact area
Torque	50%	Limited moment generation
Extrusion	54%	Weak vertical force control

Treatment duration is comparable to that of fixed appliances for mild to moderate malocclusions: 15 ± 3 months vs 14 ± 3 months (18).

Pain and quality of life

patients using clear aligners report lower pain levels. A 2023 RCT found an average reduction in VAS pain score of 1.3 units compared to traditional fixed systems (19). Discomfort peaks within the first 3 days, then subsides quickly.

Pain Intensity Over Two Weeks (VAS 0–10):

- Day 1: Fixed – 5.8, Aligners – 4.4
- Day 3: Fixed – 5.1, Aligners – 3.9
- Day 7: Fixed – 4.2, Aligners – 3.1
- Day 14: Fixed – 3.6, Aligners – 2.7

Aligners also lead to better oral hygiene and fewer soft tissue injuries, enhancing overall patient satisfaction. Their removability contributes to lower plaque accumulation and gingival inflammation, leading to improved periodontal health (20).

Periodontal and TMJ Health

Clear aligners support periodontal health due to their ease of cleaning and reduced mechanical irritation. Studies report a 32% reduction in the plaque index and a 28% reduction in the gingival index compared with fixed appliances (21).

Temporomandibular joint (TMJ) discomfort is also less common among aligner users, as occlusal interference and heavy interarch mechanics are minimized.

Biomechanics of clear aligners

aligners work through material deformation. The way forces are distributed is influenced by factors such as aligner thickness, elasticity, and the geometry of contact with the teeth. Finite element studies have shown that the stress–strain response is nonlinear and that attachment positioning significantly affects the delivered force (22).

Force Decay Over Time:

- 0h: 100%
- 12h: 68%
- 24h: 54%
- 48h: 42%
- 96h: 31%

This pattern supports the common clinical recommendation to replace aligners every 10–14 days to maintain effective, biologically safe levels of force.

Biological response

Tooth movement occurs via remodeling of the periodontal ligament (PDL) and alveolar bone. Clear aligners produce low, continuous forces that help reduce PDL hyalinization. Inflammatory markers such as IL-1β, TNF-α, and prostaglandin E2 rise temporarily but tend to normalize faster than with fixed appliances (23).

Additionally, the risk of root resorption is reduced by approximately 30%, owing to lower stress magnitudes. Aligners also preserve vascular integrity and promote overall periodontal health, supporting biologically compatible tooth movement.

Comparative biomechanics: aligners vs fixed systems

Parameter	Fixed Appliances	Clear Aligners
Force Application	Point-based	Distributed across surface
Friction	High (wire-bracket)	Minimal
Anchorage	Mechanical	Digital (attachments/software)
Root Torque Control	High	Moderate
Oral Hygiene	Moderate to Poor	Excellent
Esthetics	Low	Excellent
Compliance	Low Requirement	High Requirement

Clear aligners offer superior comfort and esthetics but are generally less effective in achieving complex root torque or extrusion movements. To overcome these limitations, hybrid approaches are being adopted, such as combining aligners with mini-screw anchorage or sectional fixed appliances (24–25).

Artificial intelligence and predictive orthodontics

artificial intelligence (AI) is transforming orthodontic treatment planning. Machine learning models are trained on extensive clinical datasets to improve the accuracy of tooth movement staging and to predict the need for refinements (26).

AI-assisted planning has been shown to increase movement accuracy by approximately 18% compared to traditional manual sequencing. Additionally, smart sensors embedded in aligners enable real-time tracking of patient compliance, with an average wear time of 19.2 ± 2.1 hours per day (27).

Smart materials and 4D printing

Next-generation aligners use shape-memory polymers that can change stiffness at body temperature, allowing the application of adaptive, continuous forces throughout treatment (28).

The advent of 4D printing introduces materials that respond to time and environmental changes—gradually adjusting their shape and mechanical properties during use.

Aligners enhanced with nanocomposite materials, such as graphene or hydroxyapatite nanoparticles, have demonstrated improved mechanical strength and antimicrobial performance. Moreover, drug-eluting aligners that release fluoride or chlorhexidine have shown a 20–30% reduction in bacterial load after two weeks of wear (29–30).

Long-term stability and relapse

post-treatment stability remains a critical concern in orthodontics. Two-year follow-up data indicate a relapse rate of approximately 11% after clear aligner therapy, which is comparable to that observed with fixed appliances (31).

The use of precision retainers and extended nighttime wear protocols contributes significantly to long-term stability. Furthermore, machine learning models are under development to predict relapse risk based on variables such as initial malocclusion, aligner wear time, and type of tooth movement (32).

Ethical and Clinical Considerations

Clear aligners have significantly expanded access to orthodontic care, particularly among adult patients, due to their discreet appearance and improved comfort. However, the high costs associated with digital workflows, proprietary software platforms, and advanced materials raise socioeconomic and ethical concerns (33).

Additionally, the rise of remote monitoring systems and teleorthodontics introduces new challenges for data privacy, patient autonomy, and the need for continuous clinical supervision. These evolving models of care necessitate updated regulatory frameworks to ensure patient safety and professional accountability (34).

Discussion

The transition from fixed appliances to removable, digitally designed systems marks a significant shift in orthodontics—from mechanical correction to predictive, biologically guided treatment. Clear aligners are not merely aesthetic solutions; they represent an integrated approach that combines material science, biomechanics, and digital planning.

Although biomechanical limitations remain—particularly in controlling torque and extrusion—ongoing advances

in artificial intelligence, thermoplastic materials, and hybrid protocols have substantially improved the clinical performance and predictability of aligners (2–3,13,26). As a result, the orthodontist's role is also evolving: from mechanical operator to digital designer and biomechanical strategist.

Future directions will likely involve real-time data integration enabling AI, biosensors, and feedback-responsive systems, allowing dynamic adjustments to force delivery and improved biological compatibility throughout treatment (35–38).

Conclusions

Clear aligners have evolved into an evidence-based, patient-centered treatment option that delivers results comparable to traditional fixed appliances across a wide range of malocclusions. Continuous innovation in digital design, smart polymers, and artificial intelligence continues to expand their clinical potential (2–3,26,28). Orthodontics is now entering a new era of digital and biological convergence. The next generation of aligners will be intelligent, adaptive, and biologically responsive—signaling not just a change in tools, but a transformation in the philosophy of care.

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