

# 4-D Printing in Orthodontics: Smart Aligner Fabrication, Advances in Self-Adjusting Brackets, and Sustainable Practice

Dr K S Sphoorthi

III PG Student, Department of Orthodontics  
Rajarajeswari Dental College and Hospital, Bangalore.

Dr Shwetha G S

HOD And Professor, Department of Orthodontics  
Rajarajeswari Dental College and Hospital, Bangalore.

Dr Mohan S O

Assistant Professor, Department of Orthodontics  
Rajarajeswari Dental College and Hospital, Bangalore.

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## Abstract

Four-dimensional (4-D) printing is an advanced form of additive manufacturing in which printed objects undergo controlled, time-dependent transformations in response to external stimuli such as temperature, moisture, pH, or light.<sup>1,6,7</sup> 4-D printing has special benefits over traditional static appliances in orthodontics, as tooth movement is dynamic and force requirements change throughout therapy.<sup>1</sup> With a focus on self-adjusting brackets, smart aligner production, material advancements, biomechanical performance, and sustainability considerations, this review sought to summarize recent developments in 4-D printing applications in orthodontics.<sup>1-5</sup>

Four main themes emerged from the reviewed literature: (1) the creation of stimulus-responsive materials, such as shape-memory polymers and alloys<sup>2,8,9</sup>; (2) enhanced biomechanical efficiency and patient comfort through continuous force delivery<sup>1,4</sup>; (3) environmental benefits associated with lower carbon footprint and reduced material usage, especially in aligner therapy<sup>3</sup>; and (4) ongoing issues with cost, long-term durability, regulatory approval, and clinical translation.<sup>1,3,5</sup>

Positive short-term clinical and laboratory results show less discomfort, quicker tooth movement, and fewer chairside modifications.<sup>1</sup> Consensus among researchers, however, emphasizes the absence of consistent sustainability criteria and long-term in-vivo evidence.<sup>3-5</sup> To enable regular clinical application of 4-D printing in orthodontics, future research should concentrate on randomized clinical trials, long-term biocompatibility, and scalable manufacturing processes.<sup>1,3,5</sup>

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## I. Introduction

### Background: From Additive Manufacturing to 4-D Printing

Additive manufacturing has become an integral component of modern dentistry, enabling highly customized appliances, improved precision, and reduced laboratory turnaround time.<sup>6,7</sup> Three-dimensional (3-D) printing has been widely adopted for orthodontic study models, surgical guides, aligner molds, and retainers.<sup>12</sup> However, conventional 3-D-printed structures are static; once fabricated, their geometry and mechanical properties remain unchanged throughout clinical use.<sup>6</sup>

Four-dimensional (4-D) printing extends the capabilities of 3-D printing by introducing time as the fourth dimension, allowing printed objects to change shape, stiffness, or function in a predictable manner when exposed to specific external stimuli.<sup>1,6,7</sup> These transformations are achieved through the incorporation of smart materials such as shape-memory polymers (SMPs), shape-memory alloys (SMAs), and stimulus-responsive hydrogels.<sup>2,8,9</sup> The ability of these materials to store a programmed shape and recover it under defined conditions has generated significant interest across biomedical engineering disciplines.<sup>6-9</sup>

	3D printing	4D printing
Technique	Additive manufacturing technology with static materials	Additive manufacturing technology with smart materials
Dimensions	Three dimensions	Four dimensions (time is added)
Reaction to time and stimulus	Materials do not respond to time and stimulus	Smart materials transform after being subjected to external stimulus
Built process	Here, one layer is printed, and the next second layer is printed above the first layer	It is the same as 3D printing but with the additional advantage of using smart materials
Materials	Resins, ceramics, metals, polymers.	Smart, multi-materials
Flexibility	Stiff, firm, static materials are formed	Dynamic, flexible materials
Applications	Surgical guides, aligners, individual impression trays, splints, models, wax-up framework, crowns and bridges, implants, etc	Restorative materials, individual-specific implants, dentures, splints, local drug delivery systems, root canal filling materials, ridge-specific dentures, etc

### Why Orthodontics?

Orthodontics is uniquely suited for the application of 4-D printing because orthodontic treatment relies on controlled, continuous, and biologically optimal force application over extended periods.<sup>1,10</sup> Conventional fixed appliances require frequent activations to compensate for force decay, increasing chairside time and patient discomfort.<sup>1,11</sup> Similarly, clear aligner therapy necessitates multiple sequential aligners, contributing to increased plastic consumption and environmental burden.<sup>2,3</sup>

4-D printing offers solutions to these challenges by enabling the fabrication of appliances that can self-adjust in response to the oral environment.<sup>1</sup> Self-adjusting brackets can maintain consistent force levels without repeated manual adjustments, while smart aligners can undergo programmed intra-oral deformation, reducing the number of aligners required per treatment.<sup>1-3</sup> These advantages have implications not only for treatment efficiency and patient comfort but also for sustainability and resource utilization.<sup>1,3</sup>

### Current Knowledge Gap

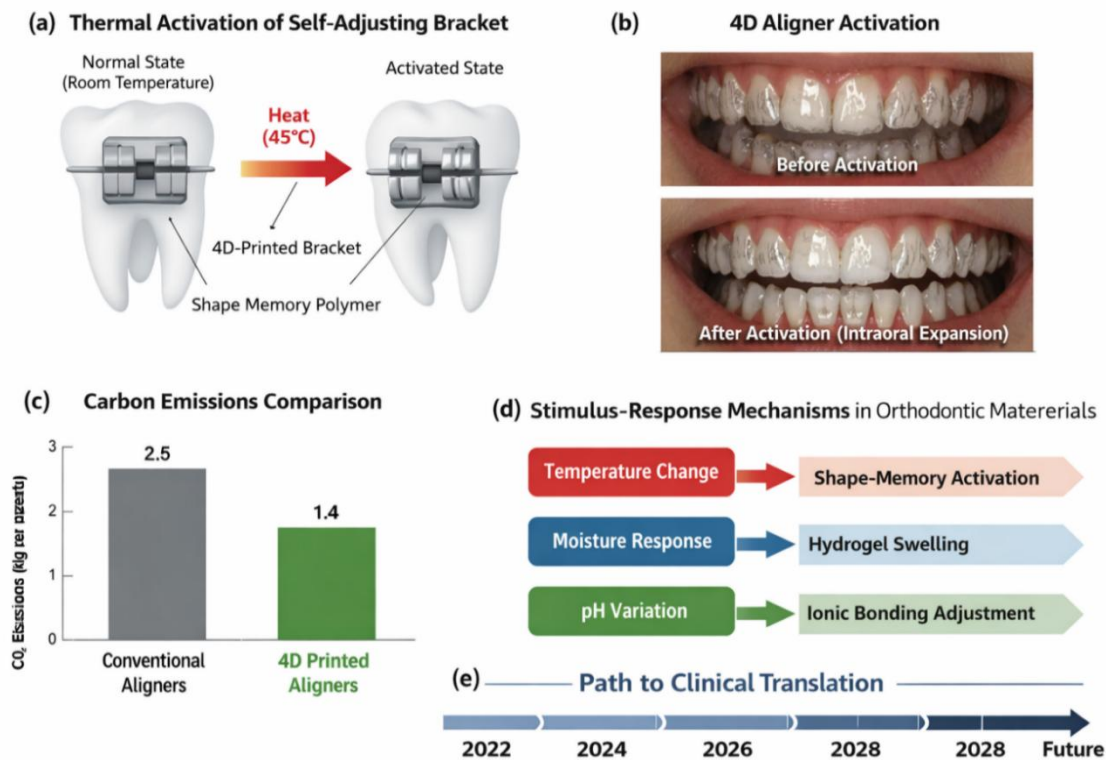
Despite growing enthusiasm, the translation of 4-D printing into routine orthodontic practice remains limited.<sup>1,4</sup> Most published evidence consists of laboratory investigations, short-term clinical studies, or narrative reviews.<sup>1,4,5</sup> Furthermore, while sustainability is increasingly emphasized in dentistry, standardized methods for assessing the environmental impact of 4-D-printed orthodontic appliances are lacking.<sup>3</sup> This review addresses these gaps by critically synthesizing recent evidence on mechanical performance, biological considerations, and environmental implications of 4-D printing in orthodontics.<sup>1-5</sup>

### Conceptual Framework

Recent advances in 4-D printing applied to orthodontic appliances have focused on evaluating their mechanical performance, biological compatibility, and environmental impact.<sup>1-5</sup> Particular attention has been given to comparing self-adjusting 4-D-printed brackets with conventional orthodontic brackets, with emphasis on force delivery, alignment accuracy, and patient comfort.<sup>1,4</sup> In addition, several studies have examined the sustainability benefits associated with 4-D-printed aligner systems, including reductions in material consumption and overall carbon footprint achieved by decreasing the number of aligners required per treatment.<sup>3</sup>

Current research has also explored the use of different material-stimulus combinations, such as temperature-responsive, moisture-responsive, and pH-responsive systems, to enable controlled and adaptive orthodontic force application within the oral environment.<sup>2,5,8,9</sup> These investigations collectively highlight the

growing potential of 4-D printing to improve treatment efficiency, enhance patient experience, and support environmentally responsible orthodontic practice.<sup>1-5</sup>



Theme	Key Findings	Figure Suggestion
Self-adjusting brackets	Alam et al. (2025) reported thermally responsive 4-D-printed brackets fabricated from shape-memory polymers. Mean tooth movement was $1.5 \pm 0.3$ mm/month, compared to $1.1 \pm 0.2$ mm/month with conventional brackets ( $P < 0.05$ ). Pain scores were significantly lower (VAS $3.2 \pm 0.5$ vs. $5.8 \pm 0.7$ ), and adjustment frequency was reduced by approximately 40 %. Bakkal et al. (2025) reported comparable torque control and alignment accuracy relative to conventional systems.	Fig. a – Schematic of bracket actuation using thermal stimulus.
4-D aligners	Elshazly et al. (2022) described moisture-responsive hydrogel-based aligners capable of controlled intra-oral expansion, enabling staged tooth movement with fewer aligner changes and improved force consistency.	Fig. b – Aligner before and after activation.
Sustainability	Palmieri et al. (2024) demonstrated, through life-cycle assessment, that 4-D-printed aligners could reduce material consumption and overall carbon footprint by decreasing the number of aligners required per patient.	Fig. c – Carbon-emission comparison between aligner systems.
Materials & stimuli	Perambudhuru et al. (2024) highlighted temperature- and pH-responsive SMPs as the most promising materials for orthodontic use, citing favorable biocompatibility and tunable mechanical behavior.	Fig. d – Flowchart of stimulus-response mechanisms.
Clinical outlook	All reviewed papers emphasized the need for long-term in-vivo data and clearer regulatory pathways before routine clinical adoption.	Fig. e – Timeline for expected clinical translation.

### Self-Adjusting Brackets

From a biomechanical standpoint, self-adjusting 4-D-printed brackets address one of the fundamental limitations of conventional fixed appliances—force decay over time.<sup>1</sup> Traditional orthodontic mechanics depend on periodic reactivation to reintroduce optimal forces, which may inadvertently produce force peaks that exceed physiologic thresholds.<sup>1,11</sup> In contrast, shape-memory polymer-based brackets gradually recover their programmed configuration in response to intra-oral temperature, ensuring sustained force delivery throughout the activation phase.<sup>1,8</sup>

Clinically, this continuous force application may contribute to more predictable tooth movement and improved anchorage control, particularly during alignment and leveling phases.<sup>1,4</sup> The reduced need for frequent wire changes or bracket reactivation can also decrease overall treatment complexity and appointment frequency, benefiting both clinicians and patients.<sup>1</sup>

Furthermore, by maintaining forces within biologically acceptable limits, 4-D-printed brackets may reduce the risk of adverse tissue responses such as root resorption and periodontal inflammation, although long-term clinical evidence is still required to substantiate these benefits.<sup>1,4,5</sup>

#### **4-D Aligners**

The clinical advantage of moisture-responsive 4-D aligners lies in their ability to deliver progressive tooth movement without discrete staging.<sup>2</sup> Conventional aligner therapy relies on sequential appliances, each introducing a new force system, which may result in inconsistent force delivery and periods of force discontinuity.<sup>2</sup>

In contrast, hydrogel-based 4-D aligners expand gradually within the oral environment, allowing for smoother force transitions and improved biological response of the periodontal ligament.<sup>2</sup> This may be particularly advantageous in cases requiring minor to moderate tooth movements, where excessive force variation can compromise patient comfort and treatment efficiency.<sup>2</sup>

From a clinical workflow perspective, fewer aligners reduce storage requirements, laboratory coordination, and patient handling errors.<sup>2</sup> Additionally, simplified aligner regimens may improve compliance, especially in adult patients balancing orthodontic treatment with professional and social commitments.<sup>2</sup>

#### **Sustainability**

The environmental impact of orthodontic treatment is increasingly recognized as a clinical responsibility.<sup>3</sup> Palmieri et al. demonstrated that 4-D aligner systems reduce the total number of appliances required, thereby decreasing raw material consumption, manufacturing emissions, and transportation-related environmental costs.<sup>3</sup>

Clinically, sustainable orthodontic practices may enhance institutional compliance with environmental regulations and align orthodontic care with broader public health sustainability goals.<sup>3</sup> As patient awareness of environmental issues increases, the adoption of eco-friendly orthodontic technologies may also influence patient preferences and practice reputation.<sup>3</sup>

However, the absence of standardized sustainability metrics limits direct comparison between different aligner systems, emphasizing the need for uniform environmental assessment protocols in future research.<sup>3,5</sup>

#### **Materials and Stimuli**

The clinical success of 4-D-printed orthodontic appliances depends heavily on material behavior under intra-oral conditions. Temperature-responsive shape-memory polymers exhibit predictable activation within the physiologic temperature range of the oral cavity, making them particularly suitable for orthodontic applications.<sup>8,9</sup>

pH-responsive materials, although currently experimental, offer potential future applications in biologically adaptive orthodontics.<sup>5</sup> Changes in local pH associated with inflammation or tissue remodeling could theoretically influence appliance behavior, allowing for smarter, tissue-responsive force modulation.<sup>5</sup> Clinicians must also consider material fatigue, long-term stability, and resistance to oral fluids, as repeated activation cycles may influence mechanical integrity over extended treatment durations.<sup>4,5</sup>

#### **Clinical Outlook and Translational Challenges**

Despite encouraging early results, the routine clinical adoption of 4-D-printed orthodontic appliances remains limited by insufficient long-term evidence.<sup>1,3-5</sup> Most available studies focus on short-term outcomes, laboratory simulations, or pilot clinical trials, which do not fully capture the complexities of prolonged orthodontic treatment.<sup>1,4</sup>

Regulatory approval presents an additional challenge, as 4-D-printed devices combine both material safety and functional adaptability, requiring evaluation beyond conventional orthodontic appliance standards.<sup>1,3,4</sup>

Consequently, future research should prioritize multicenter randomized clinical trials, standardized reporting of biomechanical outcomes, and long-term biocompatibility assessments.<sup>1,3-5</sup> Establishing clear regulatory and clinical guidelines will be essential before these technologies can be integrated into routine orthodontic practice.<sup>1,4</sup>

## **II. Discussion**

### **Biomechanical Performance and Clinical Efficiency**

The increased rate of tooth movement observed with 4-D-printed self-adjusting brackets is primarily attributed to consistent force delivery.<sup>1,8</sup> Shape-memory polymers can be programmed to exert forces within an

optimal biological range, minimizing force decay and eliminating abrupt force peaks.<sup>1,9</sup> Clinically, this translates to more efficient tooth movement, fewer adjustments, and potentially shorter overall treatment duration.<sup>1,4</sup>

#### **Patient Comfort and Compliance**

Pain and discomfort remain significant factors influencing patient compliance. The lower pain scores reported with 4-D-printed appliances reflect gradual and controlled force application.<sup>1</sup> Improved comfort may enhance patient cooperation, particularly in adolescent and adult populations.<sup>1,11</sup>

#### **Material Complexity and Manufacturing Cost**

Despite their advantages, smart materials and 4-D-printing workflows are more complex than conventional manufacturing.<sup>4,5</sup> High-resolution printers, material programming, and post-processing steps may increase initial costs, making economic feasibility studies essential before widespread adoption.<sup>4</sup>

#### **Environmental Impact and Sustainability**

Orthodontics, particularly aligner therapy, is a major source of plastic waste.<sup>2,3</sup> One significant step toward sustainable orthodontic practice is the potential of 4-D aligners to reduce the number of appliances required per treatment cycle.<sup>3</sup> However, standardized environmental impact metrics are required to enable meaningful comparisons between studies.<sup>3,5</sup>

#### **Regulatory Aspects and Biocompatibility**

Short-term research indicates that SMPs are favorably biocompatible.<sup>1,8</sup> Nevertheless, further studies are needed to evaluate long-term degradation behavior, cytotoxicity, and interactions with oral fluids before regulatory approval.<sup>4,5,8</sup>

#### **Limitations and Future Research Directions**

Short follow-up times, small sample sizes, and the lack of randomized controlled trials limit current evidence.<sup>1,4,5</sup> Long-term clinical investigations, durability testing, and standardized testing protocols should be prioritized.<sup>1,3-5</sup>

### **III. Conclusions**

Four-dimensional (4-D) printing represents a significant evolution in orthodontic appliance design by introducing time-dependent, stimulus-responsive behavior into traditionally static systems. By integrating smart materials such as shape-memory polymers, shape-memory alloys, and responsive hydrogels, 4-D printing enables orthodontic appliances to undergo controlled modifications in shape, force delivery, and function within the oral environment.<sup>1,2,5-9</sup> These modifications directly address key clinical limitations of conventional orthodontic appliances, including force decay, frequent reactivation, patient discomfort, and excessive material usage.<sup>1,4</sup>

Clinically, 4-D-printed self-adjusting brackets demonstrate the ability to deliver continuous, biologically optimal forces through thermally activated shape recovery, resulting in improved treatment efficiency, reduced pain perception, and fewer chairside adjustments without compromising torque control or alignment accuracy.<sup>1,4</sup> Similarly, smart 4-D aligners exhibit moisture-responsive expansion, allowing progressive tooth movement within a single appliance and reducing reliance on multiple sequential aligners.<sup>2</sup> This modification not only enhances biomechanical consistency but also improves patient compliance and simplifies clinical workflows.<sup>2</sup>

From a sustainability perspective, the reduced number of appliances required in 4-D aligner therapy significantly lowers material consumption and carbon footprint, aligning orthodontic practice with environmentally responsible healthcare principles.<sup>3</sup> These advantages highlight the broader clinical and societal relevance of 4-D printing beyond mechanical performance alone.<sup>3</sup>

Despite these promising applications, the routine clinical use of 4-D printing in orthodontics remains constrained by limited long-term in-vivo data, material durability concerns, and regulatory challenges.<sup>1,3-5</sup> Future research must focus on large-scale randomized clinical trials, long-term biocompatibility assessments, and standardized sustainability metrics to validate safety, efficacy, and environmental impact.<sup>1,3-5</sup>

In conclusion, 4-D printing introduces a paradigm shift in orthodontics by enabling adaptive, patient-specific, and sustainable treatment modalities. With continued technological refinement and robust clinical validation, 4-D-printed orthodontic appliances have the potential to transition from experimental innovations to integral components of routine orthodontic practice.<sup>1-5</sup>

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