

SPECIAL ISSUE: Oral Regenerative Medicine

3D printing in orthodontics: current clinical applications, challenges, and future directions

Feng Qiu¹, Jingyi Yu¹, Mengfei Xu¹, Zhimeng Lei¹, Menglong Hu², and Fulan Wei¹ ✉

¹Department of Orthodontics, School and Hospital of Stomatology, Cheeloo College of Medicine, Shandong University & Shandong Key Laboratory of Oral Tissue Regeneration & Shandong Engineering Research Center of Dental Materials and Oral Tissue Regeneration & Shandong Provincial Clinical Research Center for Oral Diseases, Jinan, 250012, China

²Shandong Huge Dental Medical Group, Rizhao, 276825, China



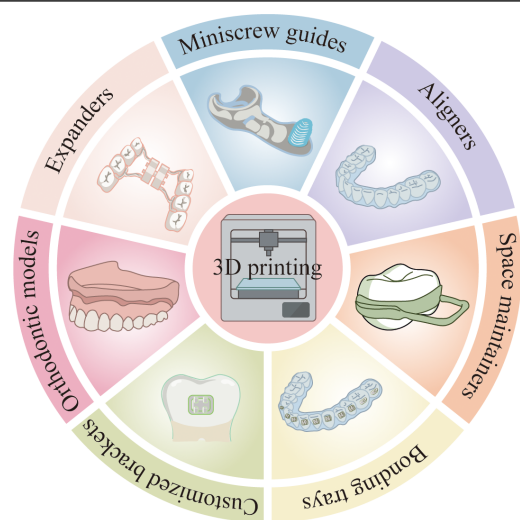
Cite This: *Oral Sci Homeost Med*, 2026, 2, 9610071



Read Online

ABSTRACT: Three-dimensional (3D) printing has become an important component of digital orthodontics and has expanded its role from model fabrication to the production of a wide range of customized appliances. This review summarizes the current clinical applications of 3D printing in orthodontics, including diagnostic models, indirect bonding trays, customized brackets, clear aligners and retainers, as well as other adjunctive devices such as miniscrew guides, space maintainers, and expanders. In addition, emerging applications such as smart materials and 4D printing are briefly discussed. Current evidence indicates that 3D printing has improved workflow efficiency, appliance customization, and manufacturing flexibility in orthodontic practice. However, the level of clinical evidence remains uneven across different applications. While some uses, such as model fabrication and indirect bonding trays, have become relatively well established, others, particularly direct-printed aligners and advanced functional appliances, are still in the early stages of clinical translation. Important challenges remain in terms of printing accuracy, material durability, esthetic stability, biocompatibility, post-processing protocols, and long-term clinical validation. Overall, 3D printing is reshaping orthodontic workflows and offers significant potential for personalized treatment, but broader clinical adoption will depend on stronger evidence, improved material performance, and more standardized manufacturing protocols.

KEYWORDS: 3D printing, additive manufacturing, orthodontics, clear aligners, indirect bonding, customized appliances



1 Introduction

Three-dimensional (3D) printing, also referred to as additive manufacturing (AM), rapid prototyping, or solid free-form fabrication, is a digitally driven manufacturing approach that constructs objects layer by layer from virtual designs using a variety of materials^[1-3]. Compared with conventional subtractive or manually fabricated methods, 3D printing offers several important advantages, including reduced material waste, shorter production time, high design flexibility, and the ability to manufacture patient-specific devices with complex geometries^[1-2]. A range of additive manufacturing technologies has been introduced into dentistry and orthodontics, including fused deposition modeling (FDM), stereolithography (SLA), digital light processing (DLP), liquid

crystal display (LCD), multi-jet printing (MJP), selective laser sintering (SLS), and continuous liquid interface production (CLIP)^[3-4].

In orthodontics, 3D printing has become an important component of the digital workflow and has substantially changed the way appliances are designed and fabricated. By integrating intraoral scanning, computer-aided design, and additive manufacturing, clinicians can produce individualized devices with improved fit, reproducibility, and manufacturing efficiency^[3-4]. To date, 3D printing has been applied to a wide spectrum of orthodontic uses, including diagnostic and working models, indirect bonding trays, clear aligners, retainers, customized brackets, and other adjunctive appliances^[4-11]. As these applications continue to expand, increasing attention has been directed toward their clinical accuracy, mechanical performance, material safety, and overall translational value in daily orthodontic practice^[5-13].

Against this background, the review aims to summarize the current clinical applications of 3D printing in orthodontics and to examine their translational status in contemporary practice.

Received: April 4, 2026; **Revised:** August 16, 2026

Accepted: September 7, 2026

✉ Address correspondence to Fulan Wei, weifl@email.sdu.edu.cn



Particular attention is given to differences in evidence maturity among various applications, ranging from relatively established uses such as diagnostic models and indirect bonding trays to emerging areas including direct-printed aligners, customized brackets, and other personalized orthodontic devices^[4-13]. In addition to highlighting current advantages, this review also discusses the major barriers that continue to limit wider clinical implementation, including material-related, mechanical, biological, and workflow-related challenges^[5,7-13]. This review seeks to provide a clinically relevant overview of where 3D printing is already useful in orthodontics, where caution is still needed, and which directions are most likely to shape future practice.

In parallel, artificial intelligence (AI) is increasingly being incorporated into digital orthodontic workflows, where it supports diagnosis, treatment planning, appliance design, and treatment monitoring^[14-20]. Accordingly, the future value of 3D printing in orthodontics will depend not only on printer and material performance, but also on how effectively these technologies are integrated into AI-assisted digital workflows^[15-20] (Fig. 1).

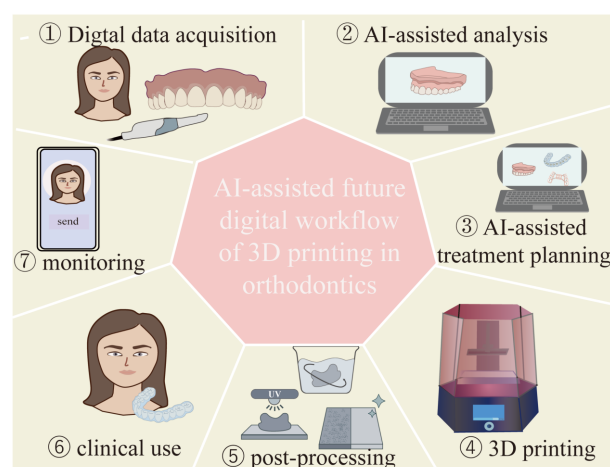


Figure 1 AI-assisted future digital workflow of 3D printing in orthodontics.

2 Literature search strategy

Relevant literature was identified through searches of PubMed/MEDLINE, Web of Science, and Scopus, supplemented by Google Scholar and manual screening of the reference lists of relevant articles. No lower publication-date limit was applied, and the search was updated through August 2026. Search terms combined concepts related to “3D printing” and “additive manufacturing” with orthodontic applications, including “orthodontic models,” “indirect bonding trays,” “clear aligners,” “retainers,” “customized brackets,” “temporary anchorage devices,” “miniscrew guides,” “expanders,” “shape-memory materials,” and “4D printing.” Additional terms related to accuracy, mechanical properties, biocompatibility, post-processing, aging, and clinical outcomes were used as appropriate. Because this article was designed as a narrative review, study selection was purposive rather than based on a formal systematic-review protocol. Priority was given to systematic reviews and meta-analyses, clinical trials and observational studies, and recent experimental studies when clinical evidence was limited. Studies were selected when they directly informed the clinical application, performance, biological safety, or translational relevance of 3D printing in orthodontics.

3 3D-printing technologies relevant to orthodontics

Several 3D-printing technologies are currently relevant to orthodontics, including FDM, SLA, DLP, LCD, MJP, SLS, and CLIP^[1-5]. These techniques differ in printing principle, resolution, production speed, surface quality, material compatibility, and cost, which in turn influence their suitability for specific orthodontic applications^[21-22]. In general, photopolymer-based technologies such as SLA, DLP, LCD, and CLIP are the most widely used in orthodontics because they provide the level of accuracy and surface detail required for dental models, transfer trays, retainers, and directly printed aligners^[21-22]. By contrast, FDM is more affordable and accessible, but its lower precision and rougher surface characteristics generally limit its use in applications in which fine detail and close fit are critical^[11-22].

From a clinical standpoint, these technologies should not be regarded as interchangeable^[21-22]. Resin-based vat-polymerization systems currently dominate orthodontic workflows because they offer the most favorable balance between dimensional accuracy, surface quality, speed, and manufacturing flexibility for appliances such as study models, indirect bonding trays, thermoforming templates, and some directly printed intraoral devices^[2-5,21-22]. MJP may provide excellent resolution and multi-material capability, whereas SLS and other powder-based approaches may be advantageous for selected functional parts requiring higher mechanical durability or metal-based fabrication routes^[1-4,22]. However, their higher equipment costs, more complex processing steps, and narrower clinical pathways have so far limited their widespread adoption in routine orthodontic practice^[21-22]. Therefore, the selection of a printing technology in orthodontics should be based not only on nominal printer resolution, but also on the intended appliance, available materials, post-processing requirements, and the practical realities of the clinical or laboratory workflow^[11-5,21].

Another important point is that printer selection alone does not determine the clinical quality of the final product^[21-24]. Recent reviews have increasingly emphasized that material composition, build orientation, layer thickness, rinsing, post-curing, and surface finishing may all influence the dimensional accuracy, surface characteristics, mechanical behavior, and biological safety of printed orthodontic devices^[5,21,23-25]. This is particularly relevant for resin-based appliances, in which inadequate post-processing may affect not only fit and surface integrity, but also residual monomer removal and intraoral safety^[23-25]. Accordingly, 3D printing in orthodontics should be understood as an integrated digital manufacturing workflow rather than as an isolated printer-dependent process^[21-24]. This perspective is especially important when comparing technologies for clinical use, because a technically sophisticated printer does not necessarily guarantee superior clinical outcomes if the associated material and post-processing protocol are not equally well controlled^[22-24] (Fig. 2).

4 Clinical established applications

4.1 Orthodontic models

Orthodontic models remain one of the most established clinical applications of 3D printing in orthodontics. They are routinely used for diagnosis, treatment planning, appliance fabrication, and treatment records, and current evidence indicates that additively

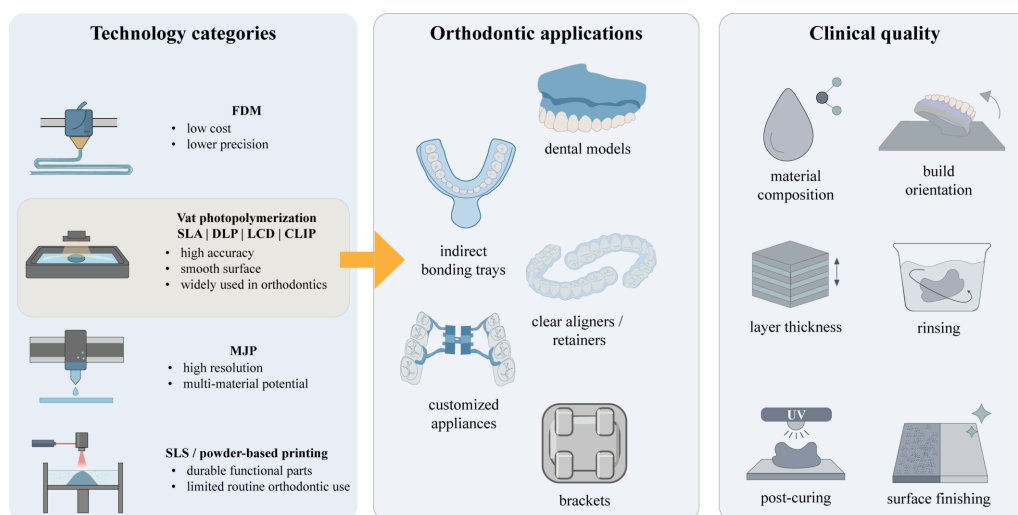


Figure 2 3D-printing technologies relevant to orthodontics.

manufactured models can achieve clinically acceptable trueness and precision when integrated into a digital workflow. Accordingly, 3D printing has shifted model fabrication from a laboratory support step to a central component of contemporary orthodontic practice, particularly the production of study models, thermoformed retainers, aligner templates, and transfer devices^[26-29].

Because orthodontic models are often used as intermediate products for subsequent appliance fabrication, their clinical value depends not only on geometric accuracy but also on downstream usability. Systematic review evidence generally favors horizontal orientation for single-model production because of advantages in time and cost efficiency, although clinically acceptable accuracy may also be obtained with other orientations depending on the printer and application^[26-30]. Recent orthodontic studies also suggest that extremely fine layer heights are not always necessary. Increased layer heights still produced accurate working models for orthodontic applications, and a clinical study found no significant difference in model accuracy or perceived retainer fit between models printed at 100 and 170 μm , while the thicker layer significantly reduced printing time. Likewise, newer evidence indicates that resin formulation and print design can significantly influence trueness and precision, underscoring that parameter recommendations cannot be transferred indiscriminately across different platforms^[28-30].

Surface quality is another clinically relevant consideration when printed models are used as thermoforming templates. The layer-by-layer fabrication process can generate surface irregularities, and printing parameters such as layer thickness and support configuration have been shown to influence the surface roughness of printed dental models^[31]. Importantly, surface characteristics of working models can be reproduced as roughness imprints on the intaglio surface of vacuum-formed retainers, indicating that the printed model serves not only as a geometric template but also influences the surface characteristics of the thermoformed appliance^[32]. Thermoforming itself also produces substantial and spatially non-uniform thinning of thermoplastic sheets, with the final thickness varying across different regions of the appliance^[33]. Therefore, pronounced surface irregularities or layer stepping on printed models may further influence local adaptation and potentially contribute to variations in the thickness distribution of thermoformed aligners and retainers, although direct quantitative

evidence linking model surface roughness to appliance thickness uniformity remains limited. From a clinical perspective, printer parameters should therefore be selected not solely on the basis of dimensional accuracy and manufacturing efficiency, but also with consideration of model surface quality when the printed models are intended for subsequent thermoforming.

Another issue that deserves greater emphasis is post-print dimensional stability. Recent studies have shown that elevated temperatures impair dimensional stability, whereas low or room-temperature storage is generally more stable; light protection may also be beneficial, depending on the material and printing system. Therefore, for precision-dependent applications such as aligner or retainer fabrication, printed models should ideally be manufactured close to the time of use and stored under controlled conditions if delayed production is unavoidable^[34-35].

4.2 Indirect bonding trays

Indirect bonding trays represent another relatively mature clinical application of 3D printing in orthodontics^[36-39]. Within a fully digital workflow, brackets can be virtually positioned on scanned dentitions, and customized transfer trays can then be designed and directly manufactured without the need for a conventional physical setup model^[36,38]. This approach improves the standardization of bracket placement and enhances the reproducibility of the bonding procedure^[36,39]. Current evidence suggests that 3D-printed trays can achieve clinically acceptable bracket transfer accuracy and, in several workflows, show results comparable to conventional transfer systems^[37-39].

From a clinical perspective, the main advantage of 3D-printed indirect bonding trays is not merely digital convenience, but the ability to transfer a planned bracket position with a high degree of consistency^[36,39-40]. However, the literature also indicates that not all dimensions perform equally well^[37-40]. Linear discrepancies are generally small and usually remain within clinically acceptable thresholds, whereas angular deviations, particularly torque, appear less predictable^[14,39-40]. In addition, transfer errors tend to be greater in the buccolingual dimension and in posterior teeth, suggesting that tray performance is influenced not only by manufacturing accuracy but also by local anatomy, bracket morphology, and tray seating during bonding^[37-38,40].

Recent studies have also shown that tray design and material

selection can significantly affect clinical performance^[11,40-42]. Randomized and comparative studies indicate that both hard and soft resins can provide clinically acceptable transfer accuracy, although soft trays may offer advantages in handling and immediate bracket retention^[40-41]. Likewise, different tray designs do not necessarily produce statistically different outcomes, but shell-type trays have shown more favorable results than bar-type trays when judged against clinical acceptability thresholds^[11]. Comparative design studies further suggest that tray geometry may influence not only transfer accuracy, but also production efficiency and clinical usability^[11,42]. These findings highlight that the success of digital indirect bonding depends on the overall tray system rather than on 3D printing alone^[11,39-42].

A further recent development is the use of AI-assisted software for tray generation, particularly in lingual indirect bonding workflows^[14]. Early clinical evidence suggests that AI-designed 3D-printed trays can achieve clinically acceptable accuracy in most dimensions, although torque control remains suboptimal and grouped trays may perform better than individual trays in some settings^[14]. Taken together, the available evidence indicates that 3D-printed indirect bonding trays are among the most clinically translatable orthodontic applications of additive manufacturing^[11,39-40]. Nevertheless, future studies should place greater emphasis on *in vivo* validation, posterior-tooth performance, lingual applications, and the standardization of accuracy assessment methods across different digital workflows^[14,39-40] (Fig. 3).

5 Emerging clinical applications

5.1 Direct-printed aligners and retainers

Direct-printed clear aligners represent one of the most rapidly developing applications of 3D printing in orthodontics^[9,43]. Unlike conventional thermoformed aligners, direct-printed aligners are fabricated directly from the digital setup without intermediate model printing and thermoforming, thereby reducing manufacturing steps and increasing design flexibility^[43-44]. This workflow may also decrease material waste and facilitate appliance customization within an in-office or lab-based digital workflow^[43]. However, recent reviews consistently indicate that high-quality prospective clinical data remain limited^[9,43].

Current clinical studies suggest that direct-printed aligners are feasible for selected mild-to-moderate malocclusions, but they do not yet justify claims of clear superiority over thermoformed aligners^[13,45-46]. In a prospective observational pilot study, the overall accuracies for torque, tip, and rotation were reported as 67.6%, 64.2%, and 72.0%, respectively, whereas transverse expansion showed an accuracy of 99.6%^[13]. A 12-month clinical evaluation further showed a significant reduction in PAR score of 86.6%, although refinement was still required in 40.8% of cases and minor

complications were observed in a small number of participants^[45]. More recently, a retrospective cohort study comparing direct-printed and thermoformed aligners found no statistically significant differences in the accuracy of torque, tip, or rotation, and both groups required similar amounts of refinement^[46]. Taken together, these findings support the clinical viability of direct-printed aligners, but they also suggest that this technology should presently be framed as a promising alternative rather than a proven replacement for conventional thermoformed systems^[13,45-46]. Notably, the field is beginning to move toward clinical testing, as a registered randomized clinical trial has been initiated to compare directly printed shape-memory aligners with thermoformed shape-memory aligners in the treatment of lower anterior crowding; however, peer-reviewed outcome data are not yet available^[47].

The growing interest in direct-printed aligners is also supported by laboratory evidence indicating potential advantages in accuracy and design customization^[43-44,48-49]. Comparative *in vitro* studies have shown greater trueness and precision for direct-printed aligners than for thermoformed aligners^[44,49]. In addition, recent experimental work suggests that retention can be modulated through thickness gradients, margin design, and other customizable geometric variables that are difficult to achieve with conventional thermoforming^[48]. Nevertheless, these advantages should be interpreted cautiously, because the mechanical behavior of direct-printed materials remains strongly dependent on resin composition and environmental aging^[49-50]. Moisture and artificial saliva exposure have been shown to adversely affect both force-related mechanical properties and dimensional fidelity, indicating that laboratory advantages do not automatically translate into predictable long-term intraoral performance^[49-50].

An additional biomechanical consideration is the time-dependent stress relaxation and force decay of directly printed aligners during intraoral use. Under sustained deformation, viscoelastic aligner materials progressively lose force, and comparative studies at 37 °C have demonstrated that this behavior is highly material-dependent rather than uniformly favorable for either printed or thermoformed systems^[51-52]. Direct-printed resins can exhibit substantially different relaxation profiles from conventional PETG- and polyurethane (PU)-based materials, while prolonged thermo-hydric exposure may also reduce the stiffness and force magnitude of some printed resins^[53]. More recently, whole-aligner testing under simulated occlusal loading showed that directly printed and thermoformed aligners generated distinct force profiles and force-decay patterns, with both material properties and appliance design influencing the resulting force system^[54]. However, current laboratory models do not fully reproduce repetitive cyclic masticatory loading, and evidence under truly dynamic intraoral conditions remains limited. Clinically, these findings indicate that initial force magnitude alone may not adequately predict force delivery throughout an aligner wear cycle; stress relaxation,

Digital workflow of 3D-printed indirect bonding trays in orthodontics

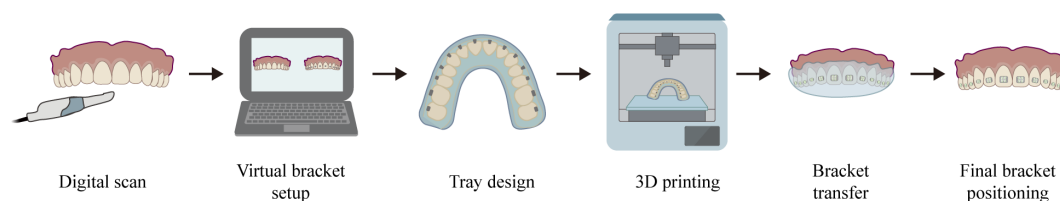


Figure 3 Digital workflow of 3D-printed indirect bonding trays in orthodontics.

repeated insertion and removal, occlusal loading, and thermohydric aging should also be considered when evaluating the biomechanical performance and wear protocols of directly printed aligners.

Biological safety deserves more explicit emphasis because it has become one of the main barriers to broader clinical translation^[55-60]. Current evidence remains limited and is still dominated by in vitro research^[55-56,59]. A systematic review suggested that direct-printed aligners may present slight cytotoxicity and, when directly compared, may show higher cytotoxicity than thermoformed aligners; importantly, no estrogenic effect and no detectable BPA release were identified in the available studies, whereas UDMA release was consistently reported and post-curing was regarded as a critical determinant of biocompatibility^[55]. A subsequent critical review likewise emphasized that the currently available evidence concerns only a few marketed resins, and that biological safety should be assessed more broadly than cytotoxicity alone, including oral soft tissue reactions and biofilm-related behavior^[56]. A systematic review focused specifically on the cytotoxicity of printed aligners concluded that the available evidence is highly heterogeneous and that cytotoxicity appears to be influenced by both resin system and post-curing duration^[59]. These findings are consistent with experimental studies showing that curing conditions and the efficacy of removing uncured resin can affect the biological profile of directly printed aligners^[57-58]. Therefore, the safety assessment of direct-printed aligners should not be limited to cell viability tests alone, but should also consider monomer release, endocrine-disrupting potential, oral soft tissue response, and biofilm adhesion under clinically relevant conditions^[55-56,59-60].

Broader literature on removable retainer materials suggests that photopolymer resins may present less favorable cytocompatibility profiles than conventional thermoplastic materials, while long-term endocrine and clinical mucosal effects remain insufficiently characterized^[60-61]. A systematic review identified only five eligible studies on direct-printed orthodontic retainers, most of which were in vitro, with only one prospective clinical investigation involving fixed retainers^[62]. More recent systematic review evidence has likewise shown that the available literature on the accuracy of printed retainers and aligners is still dominated by in vitro studies, and that the reported outcomes are highly dependent on printer type, material, and processing conditions^[63]. Accordingly, directly printed retainers may be presented as a promising extension of digital orthodontics, but they cannot yet be considered a clinically mature alternative supported by robust comparative clinical evidence^[62-63].

5.2 Customized brackets

Customized brackets represent a further extension of digital orthodontics toward individualized fixed appliance therapy^[64]. Unlike conventional preadjusted brackets, customized systems allow patient-specific modification of bracket base morphology, slot position, and prescription, and in some workflows 3D printing is used either to fabricate the definitive bracket or to generate patterns for subsequent casting^[65]. This level of customization is particularly attractive in cases with irregular tooth morphology, demanding finishing requirements, or lingual mechanics, in which standard bracket prescriptions may be less ideal. However, customized brackets should not yet be regarded as a uniformly mature clinical application of 3D printing, because the specific evidence base for fully 3D-printed brackets remains limited and is still dominated by

in vitro studies^[66].

At the clinical level, the available evidence is more robust for customized CAD/CAM bracket systems in general than for directly printed brackets specifically^[64]. A recent systematic review and meta-analysis found no significant difference between customized CAD/CAM and conventional brackets in ABO-CRE scores or number of appointments, but reported a significantly shorter overall treatment time for customized systems, with a mean reduction of approximately 4 months^[64]. These findings suggest a potential efficiency advantage for customized bracket therapy, but they should be interpreted cautiously when discussing 3D-printed brackets themselves, because current clinical studies often combine different customized workflows, indirect bonding protocols, and manufacturing routes^[64,66].

From a manufacturing and biomechanical perspective, a systematic review and meta-analysis of in vitro studies reported that the slot heights of 0.022-inch 3D-printed brackets tended to be slightly oversized, yet remained within the tolerance limits of DIN 13971-2^[66]. The review also found that 3D-printed brackets demonstrated superior dimensional accuracy compared with conventional metal, ceramic, and self-ligating brackets, although their surface roughness was generally higher. Material and printing method also appear to influence performance^[66-67]. In a study of 3D-printed zirconia brackets, both digital light processing and material jetting produced clinically acceptable dimensional outcomes, whereas material jetting showed higher trueness and precision. By contrast, an in vitro comparison of customized lingual brackets fabricated by metal 3-dimensional printing and casting showed that, although both methods achieved clinically acceptable positional accuracy, the as-fabricated 3D-printed brackets exhibited higher trueness errors, greater slot-height errors, and increased frictional force^[65]. This increased friction is particularly relevant during sliding mechanics for space closure, in which resistance at the bracket–archwire interface determines how much of the applied force is effectively available for tooth movement. A rougher printed slot surface may increase interfacial resistance and thereby reduce the efficiency of sliding or require greater applied force to achieve the intended movement^[65-66]. However, resistance to sliding is multifactorial and is also influenced by archwire material and dimensions, bracket–wire angulation, ligation, and binding; therefore, surface roughness should be regarded as an important contributing factor rather than the sole determinant of frictional behavior. Importantly, postpolishing reduced friction and eliminated significant dimensional differences between groups, indicating that post-processing is a critical determinant of clinical performance rather than a minor technical detail^[65-66]. Recent evidence on 3D-printed zirconia brackets further supports this point: vibratory polishing markedly reduced the stair-step surface morphology and lowered frictional resistance to levels comparable with stainless-steel self-ligating brackets, although clinical validation is still required^[68]. These findings highlight the importance of slot-specific surface finishing and standardized post-processing when printed brackets are intended for mechanics that rely on archwire sliding.

Bonding performance is another issue that warrants attention^[69]. A in vitro study showed that custom mesh base designs in 3D-printed brackets significantly increased shear bond strength compared with a standard base design, suggesting that bracket-base customization may become a meaningful functional advantage rather than merely a manufacturing feature^[69]. Overall, customized

brackets can be regarded as a promising and increasingly sophisticated application of digital orthodontics, but the strongest current evidence still concerns slot accuracy, frictional behavior, and bond performance rather than long-term clinical superiority^[6,64-67,69]. Future studies should therefore focus on prospective comparative clinical trials, bracket failure rates, torque expression, finishing quality, patient-reported outcomes, and cost-effectiveness before customized 3D-printed brackets can be considered a broadly validated mainstream option^[6,64,66].

5.3 Other adjunctive and emerging applications

5.3.1 Miniscrew guides

Three-dimensional printing has also expanded into adjunctive orthodontic procedures, particularly the fabrication of surgical guides for temporary anchorage device (TAD) or miniscrew placement^[70-71]. In this setting, the main clinical value of 3D-printed guides lies in improving insertion safety and positional accuracy in anatomically sensitive areas, rather than in replacing the miniscrews themselves^[71-73]. A recent systematic review and meta-analysis that included 11 studies and 652 miniscrews concluded that static computer-assisted guidance improved both the safety and accuracy of miniscrew insertion compared with freehand or radiographic-guide methods^[71]. This finding is clinically relevant because root proximity and insertion angulation remain major determinants of miniscrew complications and failure^[71,73].

Recent clinical studies further support the usefulness of digitally designed, 3D-printed guides^[72-73]. In a randomized controlled trial on anterior palatal TAD insertion, both tested 3D-printed guide designs were clinically usable, but the authors emphasized that a safety distance should still be incorporated during virtual planning to compensate for insertion deviations^[72]. Similarly, a retrospective cohort study reported a higher miniscrew success rate for the surgical-guide group than for manual placement (90.5% vs 79.1%) and a markedly lower root contact rate (0.1% vs 17.5%)^[73]. Taken together, these findings suggest that 3D-printed miniscrew guides are among the more clinically promising adjunctive applications of additive manufacturing in orthodontics, although standardization of planning parameters and broader prospective in vivo validation are still needed^[71-78].

From a clinical perspective, insertion guides appear to be particularly useful in anatomically sensitive regions, in less experienced hands, and in cases requiring highly controlled insertion paths, such as anterior palatal placement or interradiolar sites with limited safety margins^[71,73-74]. At the same time, recent clinical reports indicate that guided placement still shows measurable deviations from the virtual plan and therefore does not eliminate the need for a predefined safety distance during planning^[72,74]. 3D-printed guides showed good but still improvable accuracy, with a mean angular discrepancy of approximately 2.95° from the planned insertion axis^[74]. These findings suggest that surgical guides should be regarded as risk-reduction tools rather than as guarantees of exact implant positioning^[72,74].

Another issue that deserves consideration is the imaging and workflow burden associated with guided miniscrew insertion. Most 3D-printed guides rely on the integration of CBCT data with intraoral scans, which improves anatomical planning but also increases dependence on image registration quality and radiographic information^[71,74-75]. Recent clinical commentary has pointed out that, in selected palatal cases, guide fabrication may also

be based on the combination of intraoral scans and lateral cephalograms to reduce radiation exposure; however, this simplified approach is limited in its ability to evaluate bicortical engagement and the relationship to structures such as the incisive canal and nasal floor^[75]. Therefore, future studies should not only compare insertion accuracy, but also clarify when guided placement is truly indicated and how digital planning protocols can be optimized to balance safety, precision, and radiation exposure^[71,74-75].

5.3.2 Space maintainers

Space maintainers are another adjunctive application in which 3D printing appears increasingly relevant, especially because these appliances benefit from customization, simplified fabrication, and improved esthetics^[70,76-77]. Compared with conventional band-and-loop appliances, digitally designed and printed space maintainers may reduce laboratory steps and facilitate appliance standardization^[70,77].

The recent clinical evidence comes from a randomized clinical trial involving 62 children, in which 3D-printed band-and-loop space maintainers showed a significantly higher 9-month survival rate than conventional appliances (77.4% vs 51.6%, $p < 0.01$), while both groups showed only mild gingival inflammation and patient satisfaction exceeded 90%^[76]. At the same time, a scoping review concluded that 3D-printed space maintainers are promising because of their accuracy, child-friendly design, and manufacturing convenience, but emphasized that the overall evidence base is still sparse and methodologically heterogeneous^[77]. Therefore, 3D-printed space maintainers may be discussed as a clinically encouraging extension of digital orthodontics, but not yet as a uniformly validated replacement for conventional appliances^[76-77].

5.3.3 Expanders

Three-dimensional printing has also begun to influence maxillary expansion therapy, particularly through digitally planned and customized miniscrew-assisted rapid palatal expansion (MARPE) appliances and related auxiliaries^[70,78-81]. In contrast to traditional prefabricated designs, digitally manufactured expanders can incorporate patient-specific anatomic information from intraoral scans and CBCT data, allowing individualized screw position, appliance framework, and insertion pathways^[78-79]. This concept is especially attractive in late adolescents and adults, in whom skeletal expansion is more technique-sensitive and appliance fit is more critical^[78-80].

At present, however, the clinical evidence remains limited and somewhat heterogeneous^[78-81]. Digital planning and manufacturing offer meaningful advantages in appliance design and workflow integration, but also noted that the literature is still relatively early and diverse in methodology^[78]. Custom 3D-printed MARPE appliances may offer advantages in achieving skeletal expansion in older patients when compared with a conventional MARPE design^[79]. A prospective CBCT study of 15 patients treated with a 3D-printed customized MARPE appliance further demonstrated the feasibility of evaluating hard-tissue, soft-tissue, and airway changes over a 6-month period^[80]. In addition, a study on a 3D-printed palatal auxiliary device for maxillary protraction after palatal expansion reported clinically acceptable accuracy and suggested that such printed auxiliaries can be integrated into digitally planned expansion-based protocols^[81].

6 Future-oriented applications: 4D printing

Four-dimensional (4D) printing can be regarded as an extension of 3D printing in which printed structures are programmed to change shape, properties, or function over time in response to external stimuli, such as heat, moisture, light, or pH^[12,82]. In orthodontics, this concept has attracted growing interest because smart materials may allow appliances to adapt dynamically during treatment rather than remain geometrically static after fabrication. At present, however, 4D printing should still be considered a future-oriented and exploratory direction rather than a mature clinical application^[12,82]. The orthodontic interest in this field has centered mainly on shape-memory aligners, whereas other proposed applications, such as self-adjusting brackets, archwires, and functional appliances, remain largely conceptual.

Among the currently proposed orthodontic uses, shape-memory aligners have received the greatest attention^[83-87]. A study demonstrated that 4D-printed aligners made of shape-memory polymer were able to produce significant tooth movement on a typodont model and generated forces within a biologically acceptable orthodontic range after thermal activation^[83]. More recent material studies have further supported the distinct behavior of these systems. In 2024, shape-memory aligner material (TC-85) showed substantial shape recovery within the 30–45 °C range, whereas thermoformed materials exhibited minimal recovery^[84,87]. Perfitalign 4D aligners showed cyclic force recovery after thermal reactivation and a trend toward more bodily movement than thermoformed aligners, although the authors explicitly noted that clinical validation is still required^[85]. In addition, experimental work has shown that force systems in directly printed aligners can be modulated by thickness design, further highlighting the design flexibility of this emerging approach^[88]. Collectively, these studies suggest that the main theoretical advantage of 4D aligners lies in recoverable force delivery and the possibility of reducing the number of sequential appliances needed to achieve programmed tooth movement^[51,83-85,87]. A further practical issue is that the performance of 4D aligners depends not only on material composition, but also on activation protocol and clinical operability. Thermal reactivation is central to most currently proposed systems, and recent evidence suggests that different direct-printed shape-memory resins may exhibit distinct force decay, stiffness, and recovery profiles under thermo-hydric conditions^[53]. Therefore, future clinical translation will require not only better materials, but also clearer and more reproducible activation protocols that can be realistically implemented in daily practice.

A related clinical challenge is that the thermal response range of shape-memory aligner materials may overlap only partially with the temperatures encountered during routine intraoral use. Although TC-85 has demonstrated temperature-dependent mechanical and shape-memory behavior across approximately 30–45 °C, resting intraoral temperature is not constant and may fluctuate around or below normal body temperature^[84, 87, 88]. For materials that recover sufficiently at approximately 37 °C, intraoral conditions may support spontaneous shape recovery; however, materials requiring higher temperatures for optimal flexibility or reactivation may depend on external thermal stimulation, such as immersion in warm water^[51, 88]. Conversely, if the transition range is too close to physiological oral temperature, uncontrolled or partial activation may occur during routine wear or exposure to hot and cold beverages. These temperature-dependent effects introduce practical challenges related to the reproducibility of activation, patient adherence to heating protocols, and consistency of force delivery.

Therefore, clinically useful 4D aligners will require a carefully defined transition temperature and standardized activation protocol that provide predictable shape recovery under realistic intraoral conditions without imposing excessive dependence on patient-controlled thermal stimulation.

Another attractive aspect of 4D printing is the possibility of integrating additional functions beyond shape adaptation^[82,86,89]. A study on ClearX aligners reported that the material retained its structural and functional properties after reshaping, and that temporary transparency changes were reversible within 12 hours, supporting the feasibility of repeated thermal activation^[86]. In parallel, a 3D-printed shape-memory resin coated with green-synthesized ZnO nanoparticles exhibited enhanced antibacterial activity against *Streptococcus mutans* and *Porphyromonas gingivalis*, while also showing favorable biocompatibility trends^[82]. These developments suggest that future 4D orthodontic appliances may combine programmable mechanics with bioactive or antimicrobial functions^[82,86,89].

At present, however, these potential advantages remain largely theoretical from a clinical standpoint, because there is still insufficient evidence to conclude that 4D aligners can reliably reduce the number of treatment stages, refinement frequency, or total treatment time in real patients^[47,82,90].

Despite its promise, the current limitations of 4D printing in orthodontics are substantial. The available literature is still dominated by narrative reviews, conceptual discussions, and in vitro or typodont-based studies, with little long-term clinical evidence^[12,82-86,89-90]. Although these findings are not limited to 4D systems, emerging in vivo studies on directly printed aligners more broadly suggest that intraoral use may alter surface roughness, porosity, thickness, and mechanical behavior, indicating that laboratory performance may not fully predict clinical aging behavior^[91-94]. Biological safety also remains a critical concern. Recent evidence suggests that post-curing conditions can influence cytotoxicity, and a review on shape-memory polymers used in orthodontic aligners concluded that evidence on biocompatibility remains limited, with potential concerns related to residual monomers, degradation products, low degradability, polymer waste accumulation, and the lack of robust recycling strategies^[90]. For these reasons, 4D printing is best discussed in the context of future translational potential rather than present-day clinical routine. Future research should prioritize standardized toxicological testing, long-term intraoral performance, true clinical outcome studies, and sustainable material development before 4D-printed orthodontic appliances can be considered broadly applicable^[57-58,82,85,90-94] (Fig. 4).

7 Current limitations and future directions

7.1 Uneven evidence maturity across applications

The findings summarized in this review indicate that the clinical maturity of 3D printing in orthodontics is highly uneven across applications. Printed orthodontic models and indirect bonding trays can currently be regarded as the most mature and clinically translatable uses, because their accuracy has been repeatedly shown to be clinically acceptable and their incorporation into digital workflows is already feasible in routine practice^[11,14]. By contrast, direct-printed aligners, customized brackets, and various adjunctive appliances such as miniscrew guides, space maintainers, and digitally planned expanders remain at different stages of clinical

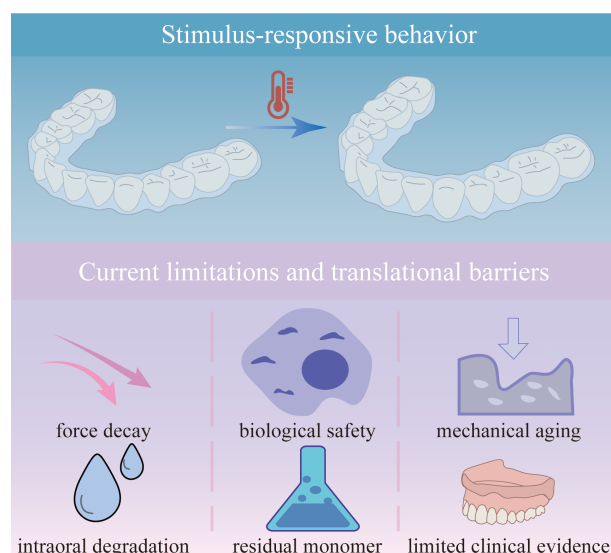


Figure 4 Stimulus-responsive behavior and translational limitations of 4D-printed shape-memory aligners in orthodontics.

translation^[76-81]. The most exploratory field is 4D printing, in which the proposed orthodontic value is conceptually attractive but the available evidence is still dominated by in vitro, typodont-based, or proof-of-concept studies^[82-87,89-94]. More broadly, recent reviews on patient-specific dental and maxillofacial devices have likewise emphasized that the translational readiness of additively manufactured appliances varies substantially according to the intended clinical application, material, and workflow complexity^[21]. To facilitate clinical interpretation of these differences, Table 1 summarizes the current evidence maturity, key post-processing considerations, and major remaining knowledge gaps for the principal orthodontic applications of 3D printing.

7.2 From technical accuracy to clinically meaningful outcomes

A key limitation in the current literature is that technical accuracy is often reported as the main outcome, whereas clinical effectiveness is assessed far less consistently. In orthodontic practice, however, a technically accurate printed object is only clinically meaningful when it improves downstream outcomes, such as bracket transfer reliability, appliance fit, movement predictability, treatment efficiency, patient comfort, appliance survival, or complication rates^[76-81]. This distinction is particularly important for direct-printed aligners and customized brackets. Although recent studies suggest promising trueness, design flexibility, and manufacturing precision, the available evidence does not yet demonstrate unequivocal clinical superiority over thermoformed aligners or conventional bracket systems^[13,45-46,64]. Future studies should therefore move beyond isolated laboratory metrics and prioritize application-specific clinical endpoints, including patient-reported outcomes and long-term treatment efficiency^[21,95].

7.3 Workflow standardization, post-processing, and quality control

Another major barrier is the lack of methodological standardization across studies. Published reports differ widely in printer type, resin composition, build orientation, layer thickness, model design, post-processing protocol, aging procedure, and outcome assessment

method^[6,9,62-67,69]. As a result, even when two studies address the same application, their findings are often difficult to compare directly^[26-30,34-36,63,66]. This problem is especially evident in studies on printed models, aligners, and brackets, where performance appears to be strongly dependent on the specific printer-material-workflow combination rather than on a single universally optimal parameter^[23,65-67,95]. Moreover, post-processing should not be regarded as a minor technical detail. Cleaning, post-curing, removal of uncured resin, and surface finishing can all influence dimensional stability, surface properties, cytotoxicity, and mechanical behavior^[25,55-58,91-92]. Greater standardization in reporting, manufacturing, and testing would therefore substantially improve the interpretability and translational value of future research^[21,23,25].

7.4 Sterilization, disinfection, and infection-control considerations

An additional issue that deserves explicit discussion is sterilization and disinfection within the clinical workflow of 3D-printed orthodontic devices, particularly for surgical guides and other appliances that may contact the oral environment during placement or delivery. In a study, autoclaving at 121 °C and low-temperature dry sterilization at 54 °C showed more favorable dimensional stability for printed surgical guides than alcohol-based spray or immersion protocols^[98]. Another investigation demonstrated that the type of LCD printer, storage duration, and steam sterilization all influenced the dimensional stability of a photopolymer resin used for surgical guides^[99]. These findings suggest that decontamination protocols should be regarded as part of the validated manufacturing workflow rather than as interchangeable final procedures. Future studies should therefore address not only microbial control, but also the effects of sterilization and disinfection on fit, dimensional fidelity, mechanical integrity, and storage-related stability of orthodontic 3D-printed devices^[97-99].

7.5 Material-related, biological, and microbiological concerns

Material-related and biological concerns also remain central limitations to broader clinical adoption. For model fabrication or transfer trays, these concerns may be less critical because the printed object is often used indirectly^[11,14,26-30,34-42]. For intraoral appliances such as direct-printed aligners, retainers, and future shape-memory devices, however, biocompatibility, residual monomer release, post-curing adequacy, surface degradation, water sorption, esthetic stability, and long-term mechanical durability become highly relevant^[23,89-96]. Recent evidence has shown that post-curing conditions can affect cytotoxicity and that intraoral aging may alter thickness, roughness, porosity, and mechanical behavior of directly printed aligners^[55-58,91-94]. In addition, recent reviews have highlighted that the biological safety of 3D-printed aligner resins should not be limited to cytotoxicity testing alone, but should also include estrogenicity, oral soft tissue reactions, and biofilm-related issues^[56]. A systematic review and meta-analysis further suggested that microbial adhesion and biofilm accumulation on 3D-printed aligners are strongly influenced by resin composition, surface roughness, post-curing, and finishing protocols, with some datasets showing higher biofilm biomass than thermoformed controls^[96]. These findings indicate that material performance under real oral conditions should be treated as a core translational issue rather than as a secondary laboratory concern^[55-58,91-94,96].

Table 1 Evidence maturity, recommended post-processing steps, and major knowledge gaps of principal 3D-printed orthodontic applications.

Application domain	Evidence maturity	Recommended post-processing steps	Major knowledge gaps
Models	Mature	Washing/cleaning; post-curing; support removal; surface finishing when required	Surface roughness–appliance thickness relationship; printer/material-specific parameter standardization; long-term dimensional stability
Indirect bonding trays	Mature	Washing/cleaning; post-curing; removal of residual resin and supports	Torque-transfer accuracy; posterior and lingual applications; effects of tray design/material; standardized accuracy assessment
Direct-printed aligners	Developing	Removal of uncured resin; post-curing; support removal; edge finishing/polishing	Long-term clinical effectiveness; force decay/stress relaxation; intraoral aging; biocompatibility; standardized post-processing
3D-printed/customized brackets	Early	Support removal; material-specific curing/sintering; surface and slot finishing/polishing; cleaning	Clinical effectiveness; sliding mechanics and friction; torque expression; bracket failure; standardized finishing protocols
TAD/miniscrew guides	Developing	Washing/cleaning; post-curing; support removal; validated sterilization/disinfection	Planning safety margins; registration accuracy; indications for guided placement; prospective clinical validation
Customized expanders	Early	Support removal; material-specific finishing/polishing; cleaning/disinfection	Long-term skeletal effects; manufacturing reproducibility; complications/failure; comparative clinical evidence

7.6 Economic, regulatory, and implementation barriers

It is also important to recognize that the clinical value of 3D printing lies not only in the printed product itself, but in the broader digital workflow in which it is embedded. In-office or laboratory-based printing may reduce reliance on conventional fabrication routes and improve customization, but these advantages are meaningful only when matched by reliable scanning, planning, manufacturing, post-processing, and quality-control procedures^[11,14,21,23,25–30,31–43,55,65–67]. At the same time, recent reviews on additively manufactured patient-specific dental devices have highlighted continuing barriers related to implementation costs, material availability, workflow reproducibility, and regulatory oversight^[21,23]. For example, a customized bracket or aligner may be digitally sophisticated, yet its practical benefit will remain limited if bonding accuracy, force delivery, material aging, or post-processing quality are inconsistent^[48–52,65–68]. Accordingly, future orthodontic applications of 3D printing should be evaluated as integrated workflows rather than as isolated printed objects^[21].

Beyond the initial acquisition of a printer, routine in-office implementation also introduces operational demands that may be underestimated when the economic advantages of additive manufacturing are considered. The transition to an in-house workflow involves a learning curve in digital design, file preparation, printer operation, resin handling, post-processing, and quality control, and insufficient technical knowledge and staff training have been identified as important barriers to implementation in dental practice^[100–101]. In addition, the total production cost extends beyond the nominal amount of printing resin used for each appliance. Equipment maintenance and calibration, dedicated washing and post-curing units, cleaning solvents and other consumables, software requirements, failed prints, and staff time required for support removal, washing, curing, finishing, and inspection all contribute to the actual cost and workload of in-office manufacturing^[21,23, 100]. These post-processing steps are particularly important for resin-based orthodontic devices because inadequate processing can compromise dimensional accuracy, surface properties, mechanical performance, and biological safety^[23–25]. Therefore, the economic feasibility of in-office 3D printing should be evaluated in terms of the entire validated workflow and total operational burden rather than printer price or material consumption alone. The balance between cost and

efficiency is also likely to depend on production volume, staff experience, workflow automation, and the specific appliance being manufactured.

Regulatory complexity is also likely to increase as 3D-printed orthodontic appliances evolve from passive, static devices toward systems with programmable mechanical behavior or bioactive and drug-releasing functions. For shape-memory devices, dynamic behavior does not in itself necessarily determine a different regulatory classification; however, the programmed transition, activation conditions, force recovery, and functional stability must be demonstrated to remain reproducible under intended and reasonably foreseeable conditions of use, increasing the burden of performance verification and validation compared with conventional static appliances^[102]. Devices incorporating antimicrobial or other pharmacologically active substances may face an additional regulatory interface. In the United States, products that combine device and drug constituents, including drug-coated or drug-eluting devices, may be regulated as combination products under 21 CFR 3.2(e), requiring consideration of the regulatory requirements applicable to both constituent parts^[103]. Under the European Medical Device Regulation (EU MDR), a device that incorporates, as an integral part, a substance that would be considered a medicinal product if used separately and whose action is ancillary to that of the device is classified as Class III under Annex VIII, Rule 14, with additional assessment of the quality, safety, and usefulness of the medicinal substance^[104]. Consequently, future bioactive or drug-releasing orthodontic appliances may require evidence not only of conventional device safety and mechanical performance, but also of release kinetics, dose consistency, substance stability, biological effects, and long-term benefit-risk. These requirements represent an important translational barrier for advanced 3D- and 4D-printed orthodontic devices and should be considered early in material and product development.

7.7 Sustainability and future translational priorities

Sustainability is another issue that deserves greater attention in future orthodontic research. Although additive manufacturing may reduce some intermediate steps and improve material efficiency in selected workflows, concerns remain regarding polymer waste, uncured resin disposal, solvent use, low degradability of some materials, and the absence of robust recycling strategies for many printed appliances^[23,86,90]. Taken together, the future development of

3D printing in orthodontics will likely depend on three priorities. First, stronger prospective clinical studies are needed, particularly for direct-printed aligners, customized brackets, printed retainers, digitally planned expanders, and other adjunctive appliances^[62-72,76-81]. Second, standardized manufacturing and testing protocols should be established to improve comparability across studies and facilitate evidence synthesis^[21,23,63,66]. Third, future research should give greater weight to long-term biological safety, intraoral aging behavior, cost-effectiveness, sustainability, and patient-reported outcomes^[12,21,89-96]. If these challenges can be addressed, 3D printing is likely to move from being a valuable digital adjunct in selected orthodontic procedures to becoming a more comprehensive platform for personalized orthodontic care.

8 Conclusion

Three-dimensional printing has become an increasingly important component of digital orthodontics and has already demonstrated clear clinical value in several areas. Among the currently available applications, printed orthodontic models and indirect bonding trays appear to be the most mature and clinically translatable, whereas direct-printed aligners, customized brackets, and various adjunctive devices are progressing rapidly but still require stronger clinical validation before broader routine adoption. 4D printing and shape-memory materials represent an even earlier stage of development and should presently be regarded as promising future directions rather than established clinical solutions. The long-term success of 3D-printed orthodontic applications will depend on more robust prospective clinical studies, better standardization of printing and post-processing protocols, and deeper understanding of biological safety, intraoral aging behavior, and material sustainability.

Acknowledgements

The research was supported by the Shandong Natural Science Foundation (Grant No. ZR2024MH061).

Data available statement

N/A

Author contribution

F.Q. and F.W. formulated the topic and drafted the manuscript. J.Y., M.X. and Z.L. revised the manuscript. M.H. polished the text. All authors read and approved the final manuscript.

Ethics approval and consent

N/A

Consent for publication

All authors have reviewed and approved the manuscript for submission.

Conflicts of interest

Author Fulan Wei is an editorial board member of this journal, but she is not involved in the peer-review or decision of this article.

References

- Tian, Y. Y.; Chen, C. X.; Xu, X. T.; et al. A review of 3D printing in dentistry: Technologies, affecting factors, and applications. *Scanning* **2021**, *2021*, 9950131.
- Jeong, M.; Radomski, K.; Lopez, D.; et al. Materials and applications of 3D printing technology in dentistry: An overview. *Dent. J.* **2023**, *12*, 1.
- Cousley, R. R. Introducing 3D printing in your orthodontic practice. *J. Orthod.* **2020**, *47*, 265–272.
- Ergül, T.; Güleç, A.; Göymen, M. The use of 3D printers in orthodontics - a narrative review. *Turk. J. Orthod.* **2023**, *36*, 134–142.
- Tsolakis, I. A.; Gizani, S.; Panayi, N.; et al. Three-dimensional printing technology in orthodontics for dental models: A systematic review. *Children Basel Switz.* **2022**, *9*, 1106.
- Elabed, I.; Zheng, Z.; Zhang, Y.; et al. The mechanical and clinical properties of customized orthodontic bracket systems-a comprehensive review. *J. Funct. Biomater.* **2024**, *15*, 299.
- Tartaglia, G. M.; Mapelli, A.; Maspero, C.; et al. Direct 3D printing of clear orthodontic aligners: Current state and future possibilities. *Mater. Basel Switz.* **2021**, *14*, 1799.
- Goracci, C.; Juloski, J.; D'Amico, C.; et al. Clinically relevant properties of 3D printable materials for intraoral use in orthodontics: A critical review of the literature. *Mater. Basel Switz.* **2023**, *16*, 2166.
- Jungbauer, R.; Sabbagh, H.; Janjic Rankovic, M.; et al. 3D printed orthodontic aligners: A scoping review. *Appl. Sci.* **2024**, *14*, 10084.
- Palone, M.; Fazio, M.; Pellitteri, F.; et al. CAD/CAM-based 3D-printed and PVS indirect bonding jig system accuracy: A systematic review, meta-analysis, and comparative analysis of hard and soft CAD/CAM transfer trays. *Eur. J. Orthod.* **2024**, *46*, ejad069.
- Karabiber, G.; Eglenden, M. N. 3D printed indirect bonding trays: Transfer accuracy of bar vs shell design in a prospective, randomized clinical trial. *Angle Orthod.* **2024**, *94*, 648–656.
- Perambudhuru, Y.; Goyal, L.; Dewan, M.; et al. Application of 4D printing in dentistry: A narrative review. *J. Adv. Periodontology Implant Dent.* **2024**, *16*, 55–63.
- Migliorati, M.; Drago, S.; Castorflorio, T.; et al. Accuracy of orthodontic movements with 3D printed aligners: A prospective observational pilot study. *Korean J. Orthod.* **2024**, *54*, 160–170.
- Hoang, V.; Vuong, T. Q. T.; Nguyen, P. H.; et al. AI-assisted design of 3D-printed lingual indirect bonding trays: A comparative evaluation of bracket transfer accuracy. *J. Clin. Med.* **2025**, *14*, 4303.
- Gracea, R. S.; Winderickx, N.; Vanheers, M.; et al. Artificial intelligence for orthodontic diagnosis and treatment planning: A scoping review. *J. Dent.* **2025**, *152*, 105442.
- Preda, F.; Elshazly, N.; Jacobs, R. AI-enhanced orthodontic treatment planning - a scoping review on evidence-based clinical application with commercial software overview. *J. Dent.* **2025**, *163*, 106112.
- Guo, X. C.; Shao, Y. H. AI-driven dynamic orthodontic treatment management: Personalized progress tracking and adjustments-a narrative review. *Front. Dent. Med.* **2025**, *6*, 1612441.
- Nordblom, N. F.; Büttner, M.; Schwendicke, F. Artificial intelligence in orthodontics: Critical review. *J. Dent. Res.* **2024**, *103*, 577–584.
- Polizzi, A.; Serra, S.; Leonardi, R.; et al. Clinical applications of artificial intelligence in teleorthodontics: A scoping review. *Med. Kaunas Lith.* **2025**, *61*, 1141.
- Tomášik, J.; Zsoldos, M.; Oravcová, L.; et al. AI and face-driven orthodontics: A scoping review of digital advances in diagnosis and treatment planning. *AI* **2024**, *5*, 158–176.
- Kouhi, M.; de Souza Araújo, I. J.; Asa'ad, F.; et al. Recent advances in additive manufacturing of patient-specific devices for dental and maxillofacial rehabilitation. *Dent. Mater.* **2024**, *40*, 700–715.

- [22] Shujaat, S.; Jacobs, R. From blueprints to reality: A narrative review of evidence-based 3D printers in dentistry. *J. Dent.* **2026**, *164*, 106174.
- [23] Tichá, D.; Tomášik, J.; Oravcová, L.; et al. Three-dimensionally-printed polymer and composite materials for dental applications with focus on orthodontics. *Polymers* **2024**, *16*, 3151.
- [24] Morali, A.; Lyros, I.; Plakias, S.; et al. Influence of different post-processing procedures on the accuracy of 3D printed dental models using vat polymerization: A systematic review. *Appl. Sci.* **2025**, *15*, 11123.
- [25] Rajasekaran, A.; Chaudhari, P. K.; Haldar, P.; et al. Are the properties of 3D printed dental materials affected by nitrogen-rich postpolymerization? A systematic review and meta-analysis. *J. Prosthet. Dent.* **2025**, *133*, 981.e1–981.e13.
- [26] Alghauli, M. A.; Almuzaini, S. A.; Aljohani, R.; et al. Impact of 3D printing orientation on accuracy, properties, cost, and time efficiency of additively manufactured dental models: A systematic review. *BMC Oral Heal.* **2024**, *24*, 1550.
- [27] Subbaiah, N. K.; Chaudhari, P. K.; Duggal, R.; et al. Effect of print orientation on the dimensional accuracy and cost-effectiveness of rapid-prototyped dental models using a PolyJet photopolymerization printer: An *in vitro* study. *Int. Orthod.* **2024**, *22*, 100902.
- [28] Atam, S.; Pereira, C. L.; Shah, H. R.; et al. Optimization of three-dimensional printing parameters for orthodontic applications. *Angle Orthod.* **2024**, *94*, 375–382.
- [29] Elshebiny, T.; Canepa, I.; Kasper, F. K.; et al. The influence of 3-dimensional printing layer thickness on model accuracy and the perceived fit of thermoformed retainers. *Am. J. Orthod. Dentofac. Orthop.* **2025**, *167*, 490–498.e3.
- [30] Bor, S.; Oğuz, F. Effect of different printing designs and resin types on the accuracy of orthodontic model. *Polymers* **2025**, *17*, 2724.
- [31] Arnold, C.; Monsees, D.; Hey, J.; et al. Surface quality of 3D-printed models as a function of various printing parameters. *Mater. Basel Switz.* **2019**, *12*, 1970.
- [32] Belayutham, S.; Wan Hassan, W. N.; Razak, F. A.; et al. Microbial adherence on vacuum-formed retainers with different surface roughness as constructed from conventional stone models and 3D printed models: A randomized controlled clinical trial. *Clin. Oral Investig.* **2023**, *27*, 3245–3259.
- [33] Elshazly, T. M.; Keilig, L.; Salvatori, D.; et al. Effect of trimming line design and edge extension of orthodontic aligners on force transmission: An *in vitro* study. *J. Dent.* **2022**, *125*, 104276.
- [34] Lee, Y.; Wang, S. M.; Yan, P. T.; et al. Effect of storage temperature on the dimensional stability of DLP printed casts. *J. Prosthet. Dent.* **2024**, *131*, 331.e1–331.e7.
- [35] Alshaibani, R. M.; Fan, Y. W.; Giordano II, R. Effect of different storage conditions on dimensional accuracy of 3D-printed dental models. *J. Prosthodont.* **2025**, *34*, 617–625.
- [36] Duarte, M. E. A.; Gribel, B. F.; Spitz, A.; et al. Reproducibility of digital indirect bonding technique using three-dimensional (3D) models and 3D-printed transfer trays. *Angle Orthod.* **2020**, *90*, 92–99.
- [37] Hoffmann, L.; Sabbagh, H.; Wichelhaus, A.; et al. Bracket transfer accuracy with two different three-dimensional printed transfer trays vs silicone transfer trays. *Angle Orthod.* **2022**, *92*, 364–371.
- [38] Bachour, P. C.; Klabunde, R.; Grünheid, T. Transfer accuracy of 3D-printed trays for indirect bonding of orthodontic brackets. *Angle Orthod.* **2022**, *92*, 372–379.
- [39] Campobasso, A.; Battista, G.; Fiorillo, G.; et al. Transfer accuracy of 3D-printed customized devices in digital indirect bonding: A systematic review and meta-analysis. *Int. J. Dent.* **2023**, *2023*, 5103991.
- [40] Schwärzler, A.; Nemec, M.; Lettner, S.; et al. 3D printed indirect bonding trays: Transfer accuracy of hard versus soft resin material in a prospective, randomized, single-blinded clinical study. *Dent. Mater.* **2023**, *39*, 1058–1065.
- [41] Wang, P. Q.; Li, W. Y.; Li, B.; et al. Comparison of bracket bonding between two CAD/CAM guided bonding devices: GBD-U vs GBD-B. *J. Dent.* **2023**, *131*, 104456.
- [42] 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**, *155*, 105616.
- [43] Koenig, N.; Choi, J. Y.; McCray, J.; et al. Comparison of dimensional accuracy between direct-printed and thermoformed aligners. *Korean J. Orthod.* **2022**, *52*, 249–257.
- [44] Knode, V.; Ludwig, B.; Retrouvey, J. M.; et al. Directly printed aligner therapy: A 12-month evaluation of application and effectiveness. *Am. J. Orthod. Dentofac. Orthop.* **2025**, *167*, 73–79.
- [45] Migliorati, M.; Posadino, M.; Provenzano, C.; et al. Accuracy comparison of orthodontic movements obtained with 3D printed and thermoformed aligners: A retrospective cohort study. *Prog. Orthod.* **2025**, *26*, 42.
- [46] Shape Memory Orthodontic Aligners. ClinicalTrials.gov NCT07431333; updated February 24, 2026; accessed March 16, 2026.
- [47] Cremonini, F.; Cappelletti, M.; Brucculeri, L.; et al. An *in vitro* comparison study regarding retention force expressed by thermoformed aligners and 3D-printed aligners with different thickness and design. *Appl. Sci.* **2025**, *15*, 1345.
- [48] Dantagnan, C. A.; Salem, C.; Charavet, C.; et al. Trueness and precision of direct-printed and thermoformed clear aligners after artificial saliva exposure: A comparative *in vitro* study. *Am. J. Orthod. Dentofac. Orthop.* **2026**, *169*, 640–653.
- [49] Shirey, N.; Mendonca, G.; Groth, C.; et al. Comparison of mechanical properties of 3-dimensional printed and thermoformed orthodontic aligners. *Am. J. Orthod. Dentofac. Orthop.* **2023**, *163*, 720–728.
- [50] Lee, S. Y.; Kim, H.; Kim, H. J.; et al. Thermo-mechanical properties of 3D printed photocurable shape memory resin for clear aligners. *Sci. Rep.* **2022**, *12*, 6246.
- [51] Cremonini, F.; Brucculeri, L.; Pepe, F.; et al. Comparison of stress relaxation properties between 3-dimensional printed and thermoformed orthodontic aligners: A pilot study of *in vitro* simulation of two consecutive 8-hours force application. *APOS Trends Orthod.* **2024**, *14*, 225–234.
- [52] Oyonarte, R.; Lagos, I. M.; Vidaurre L, F.; et al. Mechanical properties of thermoformed and direct-printed aligner materials after immersion in 37 °C water: A 14-day *in vitro* study. *Sci. Rep.* **2026**, *16*, 5864.
- [53] Wiechens, B.; Meyer-Marcotty, P.; von Waldthausen, E.; et al. Biomechanical force profiles and force decrease of direct printed versus thermoformed aligners with different trimlines: An *in vitro* analysis. *Prog. Orthod.* **2026**, *27*, 23.
- [54] Dantagnan, C. A.; Babajko, S.; Nassif, A.; et al. Biocompatibility of direct printed clear aligners: A systematic review of *in vitro* studies. *Int. Orthod.* **2025**, *23*, 101028.
- [55] Goracci, C.; Mangal, U.; Čokić, S. M.; et al. Biocompatibility and safety of 3D printing resins for orthodontic aligners: A critical review of current evidence. *Polymers* **2025**, *17*, 3060.
- [56] Iodice, G.; Ludwig, B.; Polishchuk, E.; et al. Effect of post-printing curing time on cytotoxicity of direct printed aligners: A pilot study. *Orthod. Craniofac. Res.* **2024**, *27 Suppl 2*, 141–146.
- [57] Kim, J. E.; Mangal, U.; Yu, J. H.; et al. Evaluation of the effects of temperature and centrifugation time on elimination of uncured resin from 3D-printed dental aligners. *Sci. Rep.* **2024**, *14*, 15206.
- [58] Lorusso, M.; Esperou, F.; Di Carlo, G.; et al. Cytotoxicity of printed aligners: A systematic review. *Dent. J.* **2025**, *13*, 275.
- [59] Francisco, I.; Paula, A. B.; Ribeiro, M.; et al. The biological effects of 3D resins used in orthodontics: A systematic review. *Bioeng. Basel Switz.* **2022**, *9*, 15.

- [60] Chojnacka, K.; Mikulewicz, M. Cytotoxicity and endocrine disruption in materials used for removable orthodontic retainers: A comprehensive review. *Dent. J.* **2025**, *13*, 269.
- [61] Tsoukala, E.; Lyros, I.; Tsolakis, A. I.; et al. Direct 3D-printed orthodontic retainers. A systematic review. *Children Basel Switz.* **2023**, *10*, 676.
- [62] Boo, H. S.; Sivarajan, S.; @ Nor zahidah Mohd Tahir, N.; et al. Accuracy of three-dimensionally printed retainers and aligners. *J. Orofac. Orthop./Fortschr. Der Kieferorthopädie* **2026**, *87*, 184–203.
- [63] Bardideh, E.; Kerayechian, N.; Ghorbani, M.; et al. The efficacy and effectiveness of customized CAD/CAM brackets in fixed orthodontic treatment: A systematic review and meta-analysis. *Eur. J. Orthod.* **2024**, *47*, cjae075.
- [64] Nguyen, V. A.; Trinh, K. L.; Le, T. L. A.; et al. Comparative evaluation of the accuracy of customized lingual orthodontic brackets fabricated by metal 3-dimensional printing and casting: An *in vitro* study. *Am. J. Orthod. Dentofac. Orthop.* **2025**, *168*, 542–550.
- [65] Shaadoun, R. I.; Hajeer, M. Y.; Alam, M. K.; et al. Accuracy of 3D-printed customized orthodontic bracket: A systematic review and meta-analysis of *in vitro* studies. *Int. Orthod.* **2026**, *24*, 101151.
- [66] Tang, Z.; Dai, J. T.; Yu, A. L.; et al. 3D-printed zirconia orthodontic brackets: Effect of printing method on dimensional accuracy. *Orthod. Craniofacial Res.* **2024**, *27*, 147–154.
- [67] Li, B. Y.; Wu, W. Q.; Xie, C. Y.; et al. Mechanical and surface properties of 3-dimensional-printed zirconia orthodontic brackets: An evaluation of ink-jet printing combined with vibratory polishing. *Am. J. Orthod. Dentofac. Orthop.* **2026**, *170*, 77–87.e2.
- [68] Duran, G. S.; Topsakal, K. G.; Akgün, Y.; et al. Shear bond strength of 3-dimensional-printed orthodontic brackets. *Am. J. Orthod. Dentofac. Orthop.* **2025**, *168*, 379–386.
- [69] Paľovčík, M.; Tomášik, J.; Zsoldos, M.; et al. 3D-printed accessories and auxiliaries in orthodontic treatment. *Appl. Sci.* **2025**, *15*, 78.
- [70] Santmarti-Oliver, M.; Jorba-Garcia, A.; Moya-Martinez, T.; et al. Safety and accuracy of guided interraderic miniscrew insertion: A systematic review and meta-analysis. *J. Clin. Med.* **2024**, *13*, 7697.
- [71] Hoffmann, L.; Kakoschke, T. K.; Keller, A.; et al. Accuracy of guided insertion of orthodontic temporary anchorage devices comparing two different 3D printed surgical guide designs: A randomized controlled trial. *Sci. Rep.* **2025**, *15*, 31749.
- [72] Choi, E. A.; Kim, D.; Jing, L.; et al. Effect of a miniscrew surgical guide on the success rate and root proximity of orthodontic miniscrews: A retrospective cohort study. *Korean J. Orthod.* **2025**, *55*, 167–175.
- [73] Bellochio, A. M.; Ciancio, E.; Barbera, S.; et al. Accuracy assessment of 3D-printed surgical guides for palatal miniscrew placement: A retrospective study. *Appl. Sci.* **2025**, *15*, 7836.
- [74] Iodice, G.; Ludwig, B. Insertion guide for palatal TADs: Advantages and disadvantages from the clinical point of view. *Semin. Orthod.* **2025**, *31*, 91–97.
- [75] Thakur, B.; Bhardwaj, A.; Luke, A. M.; et al. Effectiveness of traditional band and loop space maintainer vs 3D-printed space maintainer following the loss of primary teeth: A randomized clinical trial. *Sci. Rep.* **2024**, *14*, 14081.
- [76] Khan, M. K.; Peedikayil, F. C.; Kumar, A. Effectiveness of three-dimensional-printed space maintainers in pediatric dental patients: A scoping review. *J. Indian Soc. Pedod. Prev. Dent.* **2025**, *43*, 468–480.
- [77] Viet, H.; Marya, A.; Apuzzo, F. D.; et al. The clinical applications and outcomes of digital MARPE in orthodontics: A scoping review. *Semin. Orthod.* **2025**, *31*, 299–309.
- [78] Sharma, Y.; Suh, H.; Bianchi, J.; et al. Treatment outcomes of 3D-printed custom and conventional mini-implant assisted rapid palatal expanders (MARPE). *Prog. Orthod.* **2025**, *26*, 30.
- [79] Mehta, P.; Singh, A. K.; Malhotra, A.; et al. Effect of customized 3D-printed MARPE appliance on hard tissues, soft tissues, and airway: A prospective CBCT study. *J. World Fed. Orthod.* **2025**, *14*, 161–169.
- [80] Kim, J. H.; Park, J. J.; Cui, F. P.; et al. Evaluation of the accuracy of a 3D-printed palatal auxiliary device for maxillary protraction after palatal expansion. *Korean J. Orthod.* **2025**, *55*, 276–289.
- [81] Bakkal, B.; Topsakal, K. G.; Duran, G. S. New horizons in dentistry and orthodontics with 4D printing technologies 4D printing and orthodontics. *Australas. Orthod. J.* **2025**, *41*, 32–39.
- [82] Elshazly, T. M.; Keilig, L.; Alkabani, Y.; et al. Potential application of 4D technology in fabrication of orthodontic aligners. *Front. Mater.* **2022**, *8*, 794536.
- [83] Atta, I.; Bouraue, C.; Alkabani, Y.; et al. Physiochemical and mechanical characterisation of orthodontic 3D printed aligner material made of shape memory polymers (4D aligner material). *J. Mech. Behav. Biomed. Mater.* **2024**, *150*, 106337.
- [84] Xu, J. N.; Ma, Y. N.; Qiang, R. Y.; et al. Force comparison between Perfitalign 4D aligners and thermoformed aligners for mandibular incisor retraction: An *in vitro* study. *Prog. Orthod.* **2025**, *26*, 44.
- [85] Palmieri, E.; Montaina, L.; Bellisario, D.; et al. Towards green dentistry: Evaluating the potential of 4D printing for sustainable orthodontic aligners with a reduced carbon footprint. *Polymers* **2024**, *16*, 3566.
- [86] Grant, J.; Foley, P.; Bankhead, B.; et al. 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. *Prog. Orthod.* **2023**, *24*, 23.
- [87] Choi, J. Y.; Kim, H.; Kim, S. H.; et al. Mechanical and viscoelastic properties of a temperature-responsive photocurable resin for 3D printed orthodontic clear aligners. *Sci. Rep.* **2025**, *15*, 23530.
- [88] Teramoto-Lida, A.; Álvarez-Chimal, R.; Reyes-Carmona, L.; et al. 3D printing of shape memory resin for orthodontic aligners with green synthesized antimicrobial ZnO nanoparticles coatings: Toward bioactive devices. *Bioeng. Basel Switz.* **2025**, *12*, 1193.
- [89] Agrawal, S.; Naik, M. K.; Umar, D.; et al. Health and environmental hazards of shape memory polymer used in orthodontic aligners - a scoping review. *Biomater. Investig. Dent.* **2026**, *13*, 45225.
- [90] Eslami, S.; Kopp, S.; Goteni, M.; et al. Alterations in the surface roughness and porosity parameters of directly printed and Invisalign aligners after 1 week of intraoral usage: An *in vivo* prospective investigation. *Am. J. Orthod. Dentofac. Orthop.* **2024**, *165*, 73–79.
- [91] Sayahpour, B.; Zinelis, S.; Polychronis, G.; et al. Effects of intraoral aging on mechanical properties of directly printed aligners vs. Thermoformed aligners: An *in vivo* prospective investigation. *Eur. J. Orthod.* **2024**, *46*, cjad063.
- [92] Sayahpour, B.; Eslami, S.; Stuhlfelder, J.; et al. Evaluation of thickness of 3D printed versus thermoformed aligners: A prospective *in vivo* ageing experiment. *Orthod. Craniofacial Res.* **2024**, *27*, 831–838.
- [93] Šimunović, L.; Miličević, A. M.; Brenko, L.; et al. Absorption and desorption dynamics of thermoformed and 3-dimensional-printed orthodontic aligners. *Am. J. Orthod. Dentofac. Orthop.* **2025**, *168*, 466–476.
- [94] Niu, C. Y.; Li, D. W.; Zhang, Y. J.; et al. Prospects for 3D-printing of clear aligners: A narrative review. *Front. Mater.* **2024**, *11*, 1438660.
- [95] Hazko, S.; Holiel, A. A.; Bourgi, R.; et al. Microbial adhesion on 3D-printed composite polymers used for orthodontic clear aligners: A systematic review and meta-analysis of *in vitro* evidence. *J. Compos. Sci.* **2026**, *10*, 26.
- [96] Pop, S. I.; Bud, E.; János, K. M.; et al. Three-dimensional surgical guides in orthodontics: The present and the future. *Dent. J.* **2025**, *13*, 74.
- [97] Alshammari, S. M.; Alhaddad, A. J.; Marghalani, T. Y.; et al. Dimensional accuracy of a sterilized and disinfected 3D-printed surgical guide: An *in vitro* study. *Microorganisms* **2025**, *13*, 2457.

- [98] Pranno, N.; Franchina, A.; de Angelis, F.; et al. The effects of light crystal display 3D printers, storage time and steam sterilization on the dimensional stability of a photopolymer resin for surgical guides: An *in vitro* study. *Mater. Basel Switz.* **2025**, *18*, 474.
- [99] Jun, M. K.; Kim, J. W.; Ku, H. M. Three-dimensional printing in dentistry: A scoping review of clinical applications, advantages, and current limitations. *Oral* **2025**, *5*, 24.
- [100] Loges, K.; Tiberius, V. Implementation challenges of 3D printing in prosthodontics: A ranking-type Delphi. *Mater. Basel Switz.* **2022**, *15*, 431.
- [101] U.S. Food and Drug Administration. Medical devices; quality system regulation amendments. *Fed. Regist.* **2024**, *89*, 7496.
- [102] Electronic Code of Federal Regulations. Title 21, § 3.2(e): Definitions—combination product. Accessed August 16, 2026.
- [103] European Parliament and Council of the European Union. Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices. *Off. J. Eur. Union*, **2017**, *L117*, 1–175.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0), which permits reusers to distribute, remix, adapt, and build upon the material in any medium or format, so long as attribution is given to the original author(s) and the source, provide a link to the license, and indicate if changes were made. See <https://creativecommons.org/licenses/by/4.0/>

© The author(s) 2026. Published by Tsinghua University Press.



清华大学出版社
Tsinghua University Press

Scioopen