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Printing parameters for digital light processing three-dimensional printing in dentistry: A practice-oriented narrative review

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Abstract

Digital light processing (DLP) is a widely adopted three-dimensional (3D) printing technology in dentistry that utilizes digital micromirror devices for photopolymerization. The quality of DLP-printed dental products depends on printing parameters. This review synthesizes how printing orientation, support design, layer thickness, exposure time, post-processing, and their interactions influence key quality attributes, including dimensional accuracy, mechanical properties, and efficiency, with the aim of proposing practice-oriented fabrication guidance for dental products. Among the evaluated parameters, printing orientation is particularly critical because its optimal selection depends on the geometry and clinical requirements of the specific clinical product. Printing orientation directly influences printing quality through critical surface orientation, model height, and interlayer cohesion area, and indirectly affects printing quality through other printing parameters. Current research is constrained by reliance on standard specimens and oversight of parameter interactions, necessitating the development of clinical scenario-specific printing workflows and material-oriented guidelines.

Keywords: Digital light processing; Three-dimensional printing; Printing orientation; Support design; Layer thickness; Exposure time; Post-processing

1. Introduction

Additive manufacturing (AM), commonly known as three-dimensional (3D) printing, is defined as the process of joining materials to fabricate parts from 3D model data, typically in a layer-by-layer manner.[1–3] The American Society of Testing Materials standard classifies AM into seven categories based on its technical principles. In dentistry, while powder bed fusion is mainly utilized for metallic removable partial denture frameworks and implants, and material extrusion for diagnostic models, their clinical applications are often constrained by high equipment costs, rough surface, or limited dimensional accuracy.[2,4–6] Conversely, vat photopolymerization (VP) has become the leading option for dental applications, enabling the fabrication of a wide range of devices, including surgical splints, provisional restorations, and aligners.[7,8] Its relatively low equipment burden, compact footprint, and rapid workflow also make it suitable for chairside and in-office use.[9] Additionally, VP can reproduce fine anatomical details with high-dimensional fidelity and smooth surfaces, which are critical for marginal adaptation, internal fit, occlusion, and patient comfort.[10] Among VP techniques, digital light processing (DLP) has become the most prominent, currently accounting for approximately 37.5% of the dental 3D-printing market.[9,11,12]

Digital light processing employs digital micromirror devices (DMDs) to project ultraviolet light onto photosensitive resin, initiating photopolymerization and layer-by-layer curing to produce high-resolution dental products.[13] By leveraging DMD chips with millions of independently adjustable micromirrors, DLP achieves micron-level accuracy through mask projection-based exposure.[14,15] This mechanism offers a superior balance of precision, speed, and reliability, particularly for small, intricate dental products.[11,16,17] Although DLP is less suitable for large-scale objects, it offers clear advantages for dental applications that demand efficient production and high-dimensional fidelity.[18,19] In comparison, stereolithography is a mature and versatile technology, but its point-by-point laser scanning process reduces fabrication efficiency in routine dental workflows.[20] Liquid crystal display printing provides a relatively accessible and high-resolution alternative, but is limited by lower light intensity, light leakage, and the finite service life of the display panel.[21]

Despite the technical superiority of DLP, its full clinical implementation remains challenging because printing parameters are non-standardized and must be tailored to different dental products. This reflects both the patient-specific geometries of dental devices and the limited consideration of multi-parameter interactions in current studies. Accordingly, the aim of this practice-oriented review is to examine how printing parameters and post-processing steps affect the dimensional accuracy, mechanical properties, and efficiency of DLP-printed dental products, and provide practical guidance for workflow optimization in clinical practice and research.

2. Fundamentals of digital light processing in dental applications

2.1. Basic workflow of digital light processing in dental applications

In dentistry, the 3D printing fabrication of a designed product involves three essential stages: slicing, printing, and post-processing (Figure 1).[22–24] During slicing, the digital 3D model is partitioned into multiple two-dimensional cross-sections, and mask images are sent to the DMD chip, which then reflects ultraviolet light according to the pattern to cure the resin layer.[25] Subsequently, the photocurable resin is solidified in a layer-by-layer manner according to the specified parameters in the printing process until the product is complete.[13] The final stage is post-processing, including support removal, cleaning, post-curing, and surface finishing, thereby enhancing the dimensional accuracy, mechanical properties, and efficiency of the printed product.[26]

The qualities of 3D-printed dental appliances are influenced by the combined effects of the printer, printing materials, and printing process. In clinical practice, where printer settings are often fixed, the quality of the final dental products can be optimized by adjusting the printing parameters and the post-processing workflow (Table 1). The complex coupling mechanisms between printing parameters and quality metrics in DLP are systematically synthesized in Figure 2, providing a structured framework for understanding how printing orientation, support design, layer thickness, exposure time, and post-processing

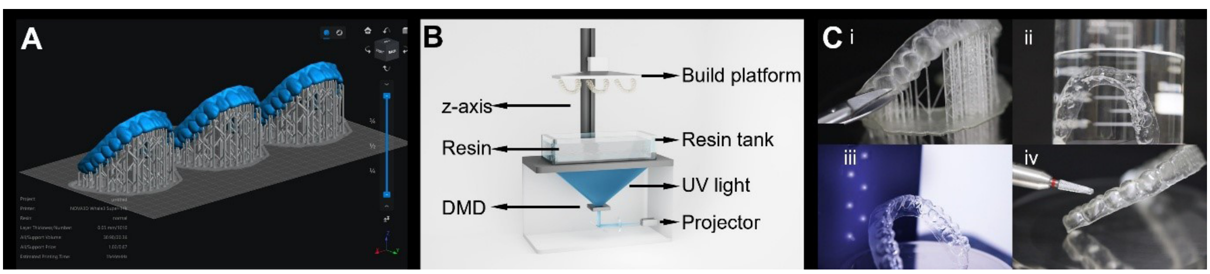

Figure 1. Workflow of DLP 3D printing in dentistry. (A) Model slicing process. (B) DLP 3D printing process. (C) Post-processing process (i) support removal, (ii) cleaning, (iii) post-curing, (iv) surface finishing (grinding and polishing).
Abbreviations: 3D: Three-dimensional; DLP: Digital light processing. DMD: Digital micromirror device. UV: Ultraviolet.

Table 1. Definitions of the three-dimensional printing process parameters

Three-dimensional printing process parameter	Definition
Printing parameters	
Printing orientation	The placement angle of the printed product on the build platform[27]
Support design	Temporary structures added to maintain the shape and stability of the printed product[28]
Overhang area	A downward-facing region of a part that extends beyond the layer beneath it and lacks sufficient support contact during fabrication, thus requiring additional support structures to prevent sagging or delamination[29]
Support tip diameter	The diameter at the very top of the support structure, where it directly contacts the model[30]
Support middle diameter	The diameter of the middle section of the support post, which determines the overall strength and rigidity of the support structure[30]
Density of supports	The quantitative measure of support points distributed per unit area of support-relevant overhang regions, often expressed via contact point spacing[31]
Exposure time	The duration of light exposure for curing a single layer[32]
Layer thickness	The thickness of each sliced layer during the layer-by-layer slicing process[33]
Post-processing	
Support removal	The mechanical or chemical removal of auxiliary support structures attached to the part[34]
Cleaning	The removal of residual material, powder, or impurities from the surface of the workpiece through physical or chemical methods[35]
Post-curing	Also known as secondary photopolymerization, a process that further cures the material through light exposure or heating[36]
Post-curing time	The required time for the material to reach the target curing state
Post-curing temperature	The ambient temperature during post-curing, which regulates the molecular reaction rate[37]
Post-curing wavelength	The wavelength of the light source used for post-curing[38]
Gaseous environment	The gaseous environment in which the printed part is placed during post-curing[39]
Surface finishing	Operations such as grinding or polishing are performed on the surface of the workpiece[40]

collectively influence dimensional accuracy, mechanical properties, and efficiency.

2.2. Comparison of dental and conventional engineering digital light processing workflows

Compared with conventional engineering DLP, dental DLP is inherently more practice-oriented because it is based on patient-specific, clinically constrained geometries and is evaluated primarily by clinical fit and functional acceptability rather than nominal dimensions alone.[41–43] Accordingly, parameter selection in dental DLP must prioritize protection of critical fitting and aesthetic areas, while material selection and post-processing are further constrained by indication-specific requirements, such as biocompatibility.[27,44,45] However, conventional engineering DLP often prioritizes dimensional tolerance, engineering

Table 2. Comparison of dental and conventional engineering digital light processing workflows

Workflow aspect	Practice-oriented dental requirements	Conventional engineering requirements
Design input	Derived from patient-specific anatomical data, with highly individualized and clinically constrained geometries[46]	Typically derived from standardized computer-aided design models or prototype geometries[47]
Primary target	Defined by clinical fit, marginal adaptation, and functional acceptability[41]	Defined primarily by dimensional tolerance and engineering performance[48]
Orientation strategy	Determined by the need to protect critical surfaces, with printing orientation and support placement adjusted accordingly[49]	Determined by the need to ensure build stability and manufacturability, with printing orientation and support placement adjusted accordingly[50]
Material selection	Selected based on clinical indication and biocompatibility[51]	Selected based on mechanical and thermal properties[47]
Post-processing	Strictly controlled to reduce residual monomer and ensure dimensional accuracy[35,52]	Allowed to accommodate broader process tolerances[53]

functionality, and broader manufacturability. These distinctions are summarized in Table 2.

2.3. Printing materials for digital light processing in dental applications

To meet dental requirements, DLP materials must provide not only adequate dimensional accuracy and mechanical strength, but also biocompatibility, aesthetics, and intraoral stability. Accordingly, materials should be regarded as integrated photocurable systems in which the resin composition, photoinitiator chemistry, and light-modulating additives collectively determine curing behavior, cytocompatibility, and application-specific suitability.[54]

Common dental DLP resins are predominantly methacrylate-based and include urethane dimethacrylate, triethylene glycol dimethacrylate, and high-viscosity polyurethane-derived macromonomers.[55] In ceramic DLP, these organic matrices also function as photocurable binders for highly filled suspensions. Depending on the indication, formulations may incorporate fillers such as barium glass or ytterbium trifluoride to improve mechanical properties, wear resistance, and radiopacity.[56] From a materials design perspective, the key requirement is to balance printability and optical control with an adequate degree of conversion, low residual cytotoxicity, and application-specific mechanical performance.

Photoinitiators are equally important because they directly affect curing efficiency, degree of conversion, and biocompatibility. In dental DLP, phenylbis(2,4,6-trimethylbenzoyl) phosphine oxide (TPO), camphorquinone, and related phosphine oxide-based systems are commonly used to initiate crosslinking under near-ultraviolet or visible light, depending on the resin formulation and irradiation wavelength.[57] Their concentration must be optimized in conjunction with the resin matrix and post-curing protocol, as it influences cure depth, mechanical properties, color stability, and residual toxicity.

Recent studies have illustrated the interplay among resin chemistry, photoinitiator concentration, and post-curing conditions in shaping dental material properties. For instance, Gavioli *et al.*[51] reported that 1 wt.% TPO combined with 30 min of post-curing produced provisional resins with balanced mechanical performance, cytotoxicity, and color stability, whereas tuning the urethane macromonomer structure has been demonstrated to improve fracture toughness without compromising flexural performance.[58]

3. Printing parameters and their impact on printing quality

3.1. Printing orientation

Prior studies have indicated that printing orientation is a key determinant of dental appliance quality, and its influence spans dimensional accuracy, mechanical performance, and production efficiency (Table 3).

In practice, this parameter primarily determines the printing orientation of the model, which in turn influences

Table 3. Summary of literature evaluating the effect of printing orientation on the printing quality and performance of three-dimensionally printed dental products

Authors	Year	Material & printer	Products	Optimal parameters	Measurement indicators	Results
Osman *et al.*[59]	2017	•NextDent C&B with RapidShape D30 DLP printer	Full-coverage crown restoration	•Printing orientation: 135°	•Dimensional accuracy (RMSE)	Printing at a 135° build angle yielded the lowest RMSE (0.049 mm) and produced the most favorable deviation pattern among all orientations
Ryu *et al.*[60]	2020	•NextDent C&B with Flashforge Hunter DLP printer	Single premolar crown	•Printing orientation: 150°, 180°	•Marginal gap (MG) •Cervical gap (CG) •Occlusal gap (OG)	Printing at 150° and 180° yielded the smallest MG, CG, and OG values, indicating improved geometric fidelity
Park *et al.*[61]	2019	•NextDent C&B with D2-120 DLP printer (Hephzibah)	Three-unit prostheses	•Printing orientation: 45°, 60° •Layer thickness: 50 μm or 100 μm	•Internal gap volume (IGV) •Absolute marginal discrepancy (AMD) •Marginal gap (MG)	When printed at 45° and 60°, the specimens demonstrated the smallest IGV and AMD, with 50 μm layers providing the smallest IGV, whereas 100 μm layers provided the best MG
Alkhateeb *et al.*[62]	2023	•NextDent C&B with ASIGA DentaTOOTH •NextDent 5100 with ASIGA MAX DLP printers	Interim three-unit fixed dental prostheses	•Printing orientation: 0°, 45° •Post-curing: 120 min	•Fracture load	Printing at a 45° orientation combined with a 120-min post-curing process achieved the highest fracture load (≈1,500 N)
Song *et al.*[63]	2023	•DENTCA Denture Base II with SprintRay Pro95	Complete denture bases	•Printing orientation: 0°, 45°, 90°	•Manufacturing accuracy (RMSE)	Printing at labial 45° and 90° achieved the best overall accuracy, with RMS values of 0.076 ± 0.010 mm and 0.078 ± 0.012 mm, respectively
Jin *et al.*[27]	2020	•NextDent Base resin with Bio3D W11 (NextDent) DLP printer	Maxillary and mandibular complete denture bases	•Printing orientation: 135°(maxillary), 100°(mandibular)	•Tissue-surface adaptation (RMSE)	Color deviation analyses showed that 135° produced the most favorable deviation pattern in the maxilla, while 100° was optimal for the mandible
Hussein *et al.*[64]	2022	•DentaCast castable resin with ASIGA MAX UV DLP printer	Partial denture frameworks	•Printing orientation: 135°(maxillary), 150°(mandibular)	•Trueness of RPD frameworks (RMSE)	135° in the maxilla (0.070 ± 0.007 mm) and 150° in the mandible (0.066 ± 0.008 mm) yielded the lowest dimensional deviations
Chaiamornsup *et al.*[65]	2022	•Dima Print Cast Q, Kulzer with Cara Print 4.0	Partial fixed dental prostheses	•Printing orientation: 0°	•Vertical marginal discrepancy •Marginal/axial/occlusal gaps via silicone replica	Printing at 0° generated the smallest discrepancies (<120 μm) and avoided over-polymerization
Hussein *et al.*[66]	2022	•Castable resin (DentaCast, ASIGA) with Max UV (ASIGA) DLP printer	Removable partial denture frameworks	•Printing orientation: 150° •Support diameters: 1.2 mm	•Accuracy (RMSE) •Printing time	Printing at 150° with thin supports resulted in the lowest RMSE (0.061 ± 0.015 mm) and the shortest printing time (172 ± 2 min)

(*Cont'd...*)

Table 3. *Continued*

Authors	Year	Material & printer	Products	Optimal parameters	Measurement indicators	Results
Ko *et al.*[67]	2021	•Model Gray resin, SprintRay with MoonRay S, SprintRay	Dental models	•Printing orientation: 30°, 60° •layer height: 20, 50 μm	•Surface deviation: standard deviation, positive deviation, negative deviation	Printing at 30° or 60°, combined with 20 μm or 50 μm layer thickness, achieved the highest accuracy, although the results across these angles were close
Tahir *et al.*[68]	2022	•SP-RH1001, SprintRay with MoonRay S, SprintRay	Implant surgical templates	•Print orientation: 0°	•Internal surface trueness & precision •Seating accuracy (vertical discrepancy)	Printing at 0° consistently produced templates with superior internal surface and seating accuracy
Dai *et al.*[49]	2023	•Freeprint Splint, Detax GmbH with UltraCraft DS, HeyGears	Standard palatal plate model	•Printing orientation: 45°	•Trueness (RMSE) •Precision (RMSE)	Printing at a 45° orientation using DLP technology produced the lowest RMSE (0.0221 ± 0.0017 μm)
Boyer *et al.*[69]	2021	•Grey V4 resin, Formlabs with Form 2 printer, Formlabs	Orthodontic aligners	•Print orientation: 90°	•Dimensional accuracy	Printing at 90° provided the highest dimensional accuracy, characterized by the smallest standard deviation (0.21 mm) and the lowest proportion of out-of-bound points (18%)
Süpple *et al.*[70]	2021	•IMPRIMO LC model resin with Asiga MAX DLP printer	Bracket transfer models	•Printing orientation: 15°, 75°	•Transfer accuracy (linear & angular deviations)	Printing at 15° and 75° showed no statistically significant differences in accuracy, and the deviations were within a clinically acceptable range
Sarmadi *et al.*[71]	2024	•LuxaPrint Ortho Plus (DMG) with 3Demax printer	Occlusal splints	•Build angle: 0°, 30°	•Trueness (RMSE) •Precision (RMSE)	Printing at 0° and 30° resulted in significantly higher trueness compared with other build angles

Abbreviations: DLP: Digital light processing; RMSE: Root mean square error; RPD: Removable partial denture.

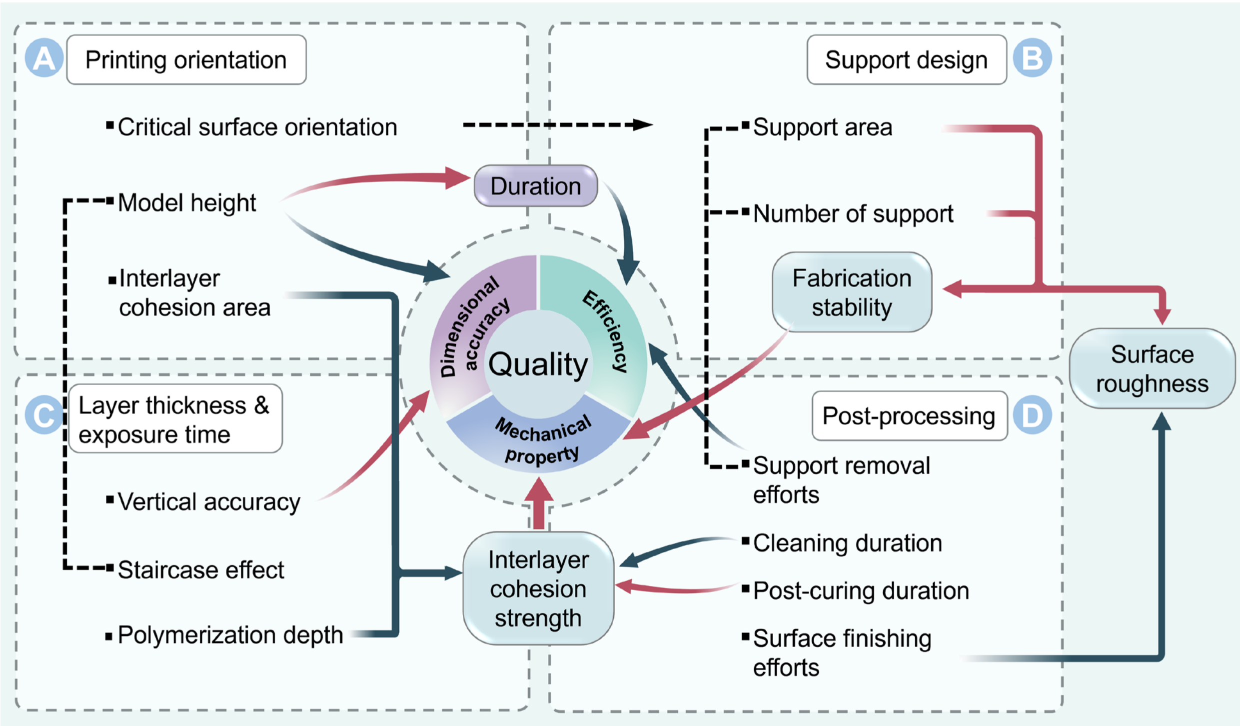

Figure 2. Correlation and interaction network of critical printing parameters influencing print quality. Red arrows indicate positive correlations, blue arrows indicate negative correlations, and black dashed lines indicate interactions between parameters. (A) Printing orientation. Orientation should be adjusted to avoid support contact on critical surfaces (e.g., functional or intaglio surface) to preserve surface quality. Increased model height due to different orientations amplifies the staircase effect, leading to reduced dimensional accuracy and efficiency. Orientation also determines the effective interlayer cohesion area: a larger area enhances interlayer cohesion strength. (B) Support design. Increasing the support area and volume improves fabrication stability and reduces deformation; however, excessive supports increase surface roughness and the effort required for removal. (C) Layer thickness and exposure time. Layer thickness is negatively correlated with vertical accuracy, and increasing the layer thickness will also make the staircase effect more pronounced. Adequate exposure time promotes polymerization depth, thereby enhancing mechanical properties. (D) Post-processing. Supports are removed after printing. Prolonged post-curing time strengthens interlayer cohesion, whereas excessive cleaning duration may detrimentally affect it. Surface finishing minimizes surface roughness.

the orientation of critical functional surfaces, the model height, and the interlayer cohesion area. Prioritizing the avoidance of support contact on critical surfaces (e.g., functional or intaglio surface) can significantly reduce the impact of support residue on the accuracy and surface roughness of critical surfaces.[72] This enhances dimensional accuracy and surface quality in clinically relevant regions. However, different orientations alter the model's height along the z-axis. Increased model height implies more printed layers, extended printing time, and potential accumulation of layer-to-layer errors, adversely affecting vertical dimensional accuracy.[67,73] Meanwhile, adjusting the printing orientation to increase interlayer cohesion area enhances interlayer bonding strength and structural stability, thereby improving both stability and mechanical properties.[74]

The impact of printing orientation on dimensional accuracy varies across different dental products. At a fundamental level, laying the model flat reduces the print height, thereby ensuring dimensional accuracy. For dental models, orientations of 30° and 60° resulted in higher accuracy, particularly when combined with smaller layer heights[67], while for crowns and denture bases, orientations of 135° and 150° improved overall printing accuracy and reduced deformation.[59,64] Occlusal splints for temporomandibular disorders exhibited the highest accuracy when printed at 0° and 30°.[75] Similarly, implant surgical templates printed at 0° showed superior intaglio surface accuracy with minimal deformation.[68] Moreover, orthodontic aligners reached optimal accuracy at 90°.[69]

Adjusting the printing orientation to increase the interlayer cohesion area can effectively enhance the mechanical properties of the model. It has been reported that an orientation of 90° generally demonstrates superior performance, as specimens printed in this orientation exhibit the highest flexural strength and modulus.[76–78]

Therefore, clinicians are advised to select the printing orientation based on the core requirements of each dental appliance.

3.2. Support design

As temporary auxiliary structures, supports provide essential mechanical reinforcement for overhangs, holes, and other complex geometries of printed products, helping to prevent warping, deformation, and sagging caused by gravity or thermal stress. Moreover, supports ensure firm adhesion of the printed products to the build platform, maintaining geometry stability throughout the layer-by-layer printing process.[64,79] Common definitions of support settings are shown in Table 1.

In dental applications, where critical surface quality and aesthetic flawlessness are paramount, support settings must be rigorously optimized. By adjusting print orientation, support structures can be avoided on critical surfaces. The basic principle of support design is to minimize the volume of support, while ensuring functional reliability.[31] Typically, support generation is mandated for areas with horizontal spans exceeding 5 mm or vertical angles surpassing 45°.[31] Excessive supports are undesirable as they degrade the surface quality, increase material consumption, and complicate post-processing.[28,80,81] Interestingly, Cao *et al.*[72] proposed a level-based scaffold structure that increased spatial efficiency by approximately 4.5-fold while preventing interference with functional or aesthetic surfaces, which provided valuable insight for developing next-generation support strategies in dental 3D printing.

The support diameter, typically divided into a tip and a middle diameter, is a critical factor influencing product surface quality and stability. Different dimensions are typically recommended for different support locations. For tip support structure, a support tip diameter of 0.4 mm is typically recommended for most dental resin materials, which provides a balance between mechanical strength and ease of removal.[82,83] For middle supports, the diameters generally range from 0.6 to 1.2 mm, and can be increased to 1.8–2.0 mm for heavy or tall regions to prevent fracture.[30] Hussein *et al.*[66] demonstrated that removable partial dentures printed with thin supports (1.2 mm) showed a dimensional deviation of 0.061 mm, significantly better than the 0.098 mm observed with thick supports (1.5 mm), which were associated with greater overall fit deviation. Support density, which can be adjusted via the touch tip distance function in the slicing software, also affects printing speed, ease of removal, and mechanical performance. Although systematic studies on the support density of dental products are limited, manufacturer guidelines commonly recommend 5 mm spacing to meet routine needs.[30] For heavy or deformation-prone regions, higher support density may be necessary.

3.3. Layer thickness and exposure time

In 3D printing, layer thickness and exposure time jointly control the curing behavior of each layer, thereby affecting the printing accuracy and mechanical performance (Table 1). Layer thickness is negatively correlated with vertical accuracy, as thicker layers exacerbate the staircase effect and reduce vertical accuracy.[17,84] However, increasing the layer thickness can also reduce the number of sliced layers, thereby improving efficiency. Additionally, extending exposure time increases polymerization and crosslink density, thereby enhancing interlayer cohesion and improving mechanical properties.[45] Yet, excessive exposure may cause overcuring and light scattering, potentially compromising dimensional accuracy.[85] Therefore, layer thickness and exposure time require coordinated control rather than isolated optimization.

For anterior restorations with high aesthetic demands, a thin layer (25 μm) is preferred to ensure superior surface quality and optical properties, thereby reducing food debris accumulation and improving oral hygiene.[86] For posterior restorations requiring high mechanical performance, a 50 μm layer thickness with a longer exposure time is recommended, although this may slightly reduce dimensional accuracy.[45,73] Typically, exposure time increases proportionally with layer thickness to ensure complete polymerization without overcuring or loss of detail. In practice, optimal exposure time generally falls within a narrow range of 3–5 s, although specific settings should be adjusted according to the manufacturer's recommendations for each resin type.[73,85]

3.4. Post-processing methods and optimization details

3.4.1. Support removal

In dental 3D printing, most products require supports, making support removal an unavoidable step in post-processing. The typical method is manual removal with scissors or other fine instruments.[26] Although time-consuming, careful handling is essential to avoid surface damage, which could compromise aesthetics and overall integrity.[87]

3.4.2. Cleaning

Due to the complex geometries, such as undercuts and pores in dental devices, residual resin is easily retained within the printed structure. Complete removal of residual resin is vital to ensure the biocompatibility of the final product. However, the cleaning process involves a critical trade-off: while insufficient washing increases cytotoxicity and compromises dimensional accuracy, excessive solvent penetration can induce material degradation and weakened interlayer adhesion, resulting in delamination and fracture.[35] Therefore, optimizing washing parameters is essential to strike a balance between biological safety, dimensional accuracy, and mechanical properties. Relevant studies are listed in Table 4.

For isopropyl alcohol (IPA), the most widely investigated solvent, studies generally suggest that a washing duration of 5–10 min achieves an optimal balance between resin removal efficiency and mechanical properties for most temporary and clear resins.[89] Xu *et al.*[90] demonstrated that a five-minute IPA wash effectively eliminated cytotoxicity caused by methyl methacrylate monomers, whereas prolonged washing (12 h) failed to further improve biocompatibility and instead caused surface cracking, drastically reducing flexural strength from 194.3 MPa to 92.1 MPa. Conversely, for tripropylene glycol monomethyl ether, Hwangbo *et al.*[35] observed that a 90-min wash duration resulted in significantly higher cell viability (80.79%) than shorter cycles (3–5 min). These discrepancies underscore the need to tailor washing protocols to specific compositions.

Additionally, specialized cleaning agents such as Yellow Magic 7 and RESINAWAY could be considered, as they have demonstrated advantages in maximizing mechanical performance. Mayer *et al.*[88] reported that specimens cleaned with Yellow Magic 7 exhibited significantly higher fracture loads than those treated with IPA. Moreover, Lambart *et al.*[91] confirmed that the specialized solvent has no measurable negative effect on surface topography, roughness, or cytotoxicity, ensuring that pursuing higher mechanical strength does not compromise biological safety or surface quality.

3.4.3. Post-curing

During photopolymerization, not all monomers fully polymerize, leaving printed products with suboptimal mechanical strength, biocompatibility, and surface quality. Post-curing addresses this limitation by exposing the prints to additional light energy. To achieve optimal results, factors such as post-curing time, temperature, wavelength, and gaseous environment must be considered (Table 1). Numerous studies have explored appropriate post-curing conditions (Table 4).

Appropriate post-curing enhances surface quality and optical properties while reducing residual monomers that may irritate oral tissues. A curing duration of 5–20 min generally meets clinical requirements for most applications.[93,101] Nevertheless, further extension of curing time increases the degree of conversion (DC) and mechanical stability, as demonstrated by Finck *et al.*[98] with 30 min dual-wavelength curing and by Kirby *et al.*[52], who reported significantly higher DC after 45 min compared with 15 min. However, prolonged curing time may reduce dimensional accuracy due to resin shrinkage during crosslinking.[102] Therefore, practitioners are advised to extend curing durations when feasible to maximize mechanical integrity, while carefully balancing the pursuit of optimal geometric stability and clinical workflow efficiency.

Moderate thermal assistance promotes polymerization and enhances strength and hardness, with optimal curing temperatures consistently reported between 40 °C and 80 °C.[90,93,97] Topsakal *et al.*[99] showed that curing at 60 °C for 30 min achieved color stability comparable to longer protocols, while excessive temperatures may cause thermal stress or warpage.[103] Efficient curing also requires wavelength matching to resin photosensitivity. Moreover, nitrogen-protected post-curing effectively suppresses oxygen inhibition, leading to higher DC, improved dimensional accuracy, enhanced wear resistance, and better biocompatibility.[39,94,100] Manoukakis *et al.*[96] reported a rapid DC increase to >96% within 1 min under nitrogen. Sahrir *et al.*[95] reported that optimized irradiance further contributes to curing efficiency, with 210 mW/cm^2 for 10 min yielding the highest trueness in fixed dental prosthesis. Overall, balanced curing durations, moderate thermal assistance, wavelength-matched irradiation, and nitrogen-protected environments constitute the most effective strategy for producing clinically reliable dental 3D printed restorations.

In clinical practice, however, post-curing protocols should be individualized according to treatment priorities: when mechanical strength and durability are paramount, more intensive post-curing is appropriate, whereas cases requiring dimensional fidelity or long-term flexibility may benefit from avoiding excessive curing conditions, particularly prolonged exposure time or elevated temperature.

3.4.4. Surface finishing

Surface finishing, as the final stage of post-processing, is critical for determining the ultimate quality of dental products. By effectively reducing surface roughness, this step minimizes microbial adhesion while enhancing aesthetic appearance and patient comfort.[84,104]

Table 4. Summary of literature evaluating the effect of cleaning and post-curing conditions on three-dimensionally-printed dental products

Procedure	Author	Resin	Specimen	Optimal condition	Key effect
Cleaning	Mayer *et al.*[88]	NextDent C&B MFH	Three-unit fixed dental prostheses	Solvent product: Yellow Magic7, Bradley Systems Major ingredients: a water-based solution containing alcohol, C12–18, ethoxylated and propoxylated (1–3%), 1-propoxypopan-2-ol (1–3%), sodium xylenesulphonate (1–3%), and dodecyldimethylamine oxide (0.3–1%) Time: 5 min	Increases fracture load and wear resistance, reduces surface roughness
	Jang *et al.*[89]	Vericom MAZIC D TEMP	Disk-shaped specimen: 2 mm (thickness) and 10 mm (diameter)	Solvent product: IPA, Vaxxen Labs Major ingredients: Isopropanol 99% Time: 10 min	Effectively removes residual monomers, improving the degree of conversion and flexural strength
	Hwangbo *et al.*[35]	NextDent C&B MFH	Bar-shaped specimen: 25 × 2 × 2 mm; disk-shaped specimen: 2 mm (thickness) and 9 mm (diameter)	Solvent product: TPM, manufacturer not specified Major ingredients: Tripropylene glycol monomethyl ether (95%) Time: 90 min	Reduces toxicity and improves biocompatibility, but requires longer cleaning time
	Xu *et al.*[90]	Dental LT Clear Resin V1	Bar-shaped specimen: 30 × 5 × 5 mm; disk-shaped specimen: 2 mm (thickness) and 14 mm (diameter)	Solvent product: IPA, SAV LP GmbH Major ingredients: Isopropanol 100% Time: 5 min	Quickly removes residual resin while maintaining mechanical properties
	Lambart *et al.*[91]	FREEPRINT splint 2.0	Bar-shaped specimen: 30 × 5 × 5 mm; disk-shaped specimen: 1.5 mm (thickness) and 10 mm (diameter)	Solvent product: IPA, manufacturer not specified Major ingredients: Isopropanol 99.9% Time: 6 min	Low toxicity, but may reduce flexural strength
	Scherer *et al.*[92]	NextDent C&B MFH	Bar-shaped specimen: 25 × 2 × 2 mm	Solvent product: RESINAWAY, Monocure 3D Major ingredients: 30–60% propylene glycol, 30–60% dipropylene glycol dimethyl ether, <10% alcohol C12–14 ethoxylated propoxylated Time: 8 min	Water-based solution reduces residue, suitable for resins containing inorganic fillers

(*Cont'd...*)

Table 4. *Continued*

Procedure	Author	Resin	Specimen	Optimal condition	Key effect
Post-curing	Jindal *et al.*[93]	Dental long-term clear resin	Clear dental aligner	Wavelength: 405 nm Time: 15–20 min Gas environment: Nitrogen atmosphere Temperature: 80 °C	Significantly increases compressive strength and enhances elastic modulus
	Özden *et al.*[94]	Senertek P-CrownV3 Ceramic; VarseoSmile Crown Plus; Saremco Print Crowntec;	Dental inlays	Wavelength: 480 nm, 530 nm Flash Count: 4,000 flashes: generally optimal across resins; 6,000 flashes: Bego resin specifically Device: Otoflash G171 Gas environment: 1.5 bar nitrogen atmosphere Temperature: Not monitored	The optimized protocol achieved the highest total overlap ratio (89.81 ± 0.5%) with optimal trueness, maintained low RMS (0.096 ± 0.02 mm), and improved resin compatibility, thereby enhancing clinical fit and longevity of dental inlays
	Sahrir *et al.*[95]	Light-polymerizing FDP resin	Three-unit fixed dental prostheses	Wavelength: 405 nm Light intensity: 210 mW/cm^2 Time: 10 min Gas environment: air Temperature: 29.0 ± 0.5 °C (Not controlled)	Exposure at 210 mW/cm^2 yielded the highest trueness (57.6 ± 2.1 μm), reduced deformation, maintained compressive strength (1,264.92 ± 39.06 N), and was identified as the recommended post-curing light intensity
	Manoukakis *et al.*[96]	Tera Harz TC-85DAC resin	Full arch aligner	Wavelength: 405 nm Irradiance: 1,000 mW/cm^2 UV irradiance Time: 1 min Gas environment: Nitrogen atmosphere Temperature: Not specified	Nitrogen atmosphere enabled rapid early DC increase (96.26% at 1 min), reaching 97.74% at 20 min, whereas oxygen significantly inhibited early free-radical polymerization, yielding lower DC at 1 min ($p < 0.001$)
	Perea-Lowery *et al.*[97]	IMPRIMO LC Denture	Bar-shaped specimen: 10 × 65 × 3.3 mm	Wavelength: 380–510 nm Time: 30 min Gas environment: Air Temperature: 40 °C	Balances flexural strength and dimensional stability while avoiding high-temperature deformation
	Finck *et al.*[98]	Provisional resin: Prizma 3D BioProv; long-term resin: Prizma 3D Bio Crown	Bar-shaped specimen: 24 × 5 × 2.5 mm; V-shaped notch: 0.4 mm (bottom width), 2.5 mm (height)	Wavelength: 405 nm, 365 nm Time: 30 min Power: 40W Device: Anycubic Wash and Cure Gas environment: Not specified Temperature: Not specified	Optimized post-curing increased fracture toughness versus five-minute curing, enhanced the C=C double bonds conversion degree of DLP-printed provisional resins, improved thermal stability, reduced residual monomers, and promoted homogeneous polymer network formation
	Topsakal *et al.*[99]	BioMed clear resin	Disk-shaped specimens: 1 mm (thickness) and 15 mm (diameter); 2 mm (thickness) and 15 mm (diameter)	Time: 30 min Temperature: 60 °C Device: Form Cure tank Wavelength: Not specified Gas environment: Not specified	Post-curing produced tooth-like color values (L*, a*, b*) within clinical acceptability, showed comparable performance to manufacturer-recommended 60-min curing, shortened processing time, and reduced yellowing with improved color stability

(Cont'd...)

Table 4. *Continued*

Procedure	Author	Resin	Specimen	Optimal condition	Key effect
	Bouchema *et al.*[100]	NextDent Ortho Flex; Freeprint Ortho Detax; Graphy TC-85DAC;	Tensile test specimens: EN ISO 527-2 type 5A; leaching/cytotoxicity test specimens: 1 cm² surface area, 1 mm thickness	Wavelength: 385–405 nm Time: NextDent Ortho Flex: ≥6 min; Graphy TC-85DAC: 14 min Gas environment: 1.5 bar nitrogen atmosphere Device: Tera Harz Cure	Post-curing reduced leachables and residual photoinitiators, increased cell viability (>76%), confirming improved biocompatibility, enhanced thermal stability, optimized tensile strength and stiffness with moderate ductility, and stabilized polymer networks against aging
Post-curing	Wada *et al.*[39]	KeySplint®hard; KeySplint®soft	Bar-shaped specimens: 3.5 × 10 × 60 mm	Flash count: 2,000 flashes Wavelength: Not specified Gas environment: Nitrogen atmosphere Temperature: Not specified	Nitrogen post-curing enhanced microwear resistance of DLP-printed hard resins, improved nano-wear resistance across materials and printers, and increased overall wear resistance under a protective nitrogen atmosphere
	Kirby *et al.*[52]	MSLA dental modeling resin	Bar-shaped specimens: 10 × 4 × 2.5 mm	Wavelength: 365 nm, 385 nm, 405 nm Power: 60 W Time: 45 min Gas environment: air Temperature: Not specified	Phrozen Cure V2 achieved the highest mean degree of conversion (69.6%) at 45-min curing, significantly higher at 45 min than 15 min ($p < 0.001$)

Abbreviations: 3D: Three-dimensional; DC: Degree of conversion; DLP: Digital light processing; FDP: Fixed dental prosthesis; IPA: Isopropanol; MFH: Microfilled hybrid; MSLA: Masked stereolithography apparatus; RMS: Root mean square; TPM: Tripropylene glycol monomethyl ether; UV: Ultraviolet.

In clinical practice, the typical procedure comprises three sequential steps. First, the printed surface is sanded with 120-grit sandpaper to remove support residues and irregularities. Next, a wool wheel mounted on a polishing machine is used for pre-polishing to level the surface. Finally, a brightener, along with a universal plastic polishing paste, is applied to achieve a smooth, aesthetic surface.[105]

4. Clinical implications and practical guidelines

4.1. Printing efficiency and its influence on clinical workflow

Printing efficiency in clinical and laboratory dental applications depends mainly on the number of prints per build and the total printing time. The number of prints is strongly influenced by the printing orientation. By optimizing the spatial arrangement of models on the build platform, more products can be fabricated in a single printing cycle. Printing time, on the other hand, is determined by the product of the number of slices (N_{slice}) and the exposure time per layer (t_{exposure}), as expressed in **Equation 1**. The number of slices depends on the ratio of model height (H) to layer thickness (L_t), as shown in **Equation 2**. Consequently, increases in model height through orientation changes or reductions in layer thickness for higher resolution both significantly increase the number of slices, thereby prolonging the total printing time. Similarly, longer exposure time directly extends the printing duration.

$$[T_{\text{total}} = N_{\text{slice}} \times \left(t_{\text{exposure}} + t_{\text{plate moving}}\right) + t_{\text{first layer exposure}}] \quad (1)$$

$$[N_{\text{slice}} = \frac{H}{L_t}] \quad (2)$$

Song *et al.*[63] demonstrated that printing orientation substantially affects total build time. Models printed at 0° required only 79 min, whereas those at 90° took up to 208 min, approximately three times longer.[63] This discrepancy was primarily due to the increased model height at the 90° orientation, which led to a significantly higher number of slices and consequently extended the printing duration.

These findings have practical implications for clinical workflow. As illustrated in Figure 3, the 0° orientation is recommended when rapid fabrication of a single dental arch is desired, as it significantly reduces printing time. Conversely, for clinical scenarios requiring the simultaneous production of multiple arches, the 90° orientation may be preferred, as it allows for more models to be accommodated on the build platform, thereby improving overall efficiency.

4.2. Common problems in clinical practice and solutions

In photopolymerization-based 3D printing, six common issues are typically encountered (Figure 4; Table 5): build plate adhesion failure, delamination, surface roughness, support failure, dimensional inaccuracies, and mechanical issues.

Build plate adhesion failure is often attributed to improper leveling or insufficient bottom exposure, preventing the initial layers from bonding firmly to the build plate.[53,106] Delamination is usually associated with inadequate exposure, rapid lifting, or weak supports.[53,107–109] Surface roughness commonly results from miscalibrated exposure settings, resin contamination, or incomplete cleaning. Support failures typically occur due to suboptimal support design, which may cause breakage or removal difficulties.[104,110] Dimensional inaccuracies may arise from overexposure, resin sedimentation, or environmental fluctuations such as changes in temperature or humidity.[76] Finally, mechanical issues are often linked to loose z-axis screws or worn components, compromising printing stability and precision.[106] Therefore, key strategies to minimize printing failures and enhance overall quality include proper calibration of exposure and leveling, along with optimized support design, standardized resin handling, and regular equipment maintenance.

4.3. Regulatory and technical considerations

Although dental DLP has advanced rapidly, its regulatory and technical framework remains underdeveloped. Most existing dental standards were established for conventional materials and manufacturing routes and therefore do not adequately address the distinctive features of 3D printing or the material–software–process interactions involved in DLP fabrication.[1] As DLP-printed dental devices are already entering clinical and commercial use, this gap complicates the assurance of safety, efficacy, and quality. Regulatory frameworks tailored to dental DLP are therefore needed, with particular attention to material selection, software validation, and control of the overall manufacturing workflow.

At the material level, current International Organization for Standardization (ISO) standards provide only partial, indication-specific guidance for dental polymers, such as ISO 4049 for restorative polymer-based materials and ISO 20795-1 for denture base polymers.[111,112] For dental DLP, resins should demonstrate biocompatibility, suitability for the intended indication, and documented safety and performance. Although ingredients such as urethane dimethacrylate, triethylene glycol dimethacrylate, barium glass, and TPO are commonly used in commercial systems, regulatory approval applies to the final resin formulation or device for a specified intended use, rather than to individual ingredients.[55–57]

At the workflow level, software for 3D printing is regulated by two guidance documents from the United States Food and Drug Administration, which standardize the full workflow, including the design of digital models, slicing, printer control, and post-processing, and require their accuracy, reliability, and consistency.[113–115] Nevertheless, no specific regulations target dental 3D printing software, making the establishment of dedicated standards for clinical standardization urgently needed.

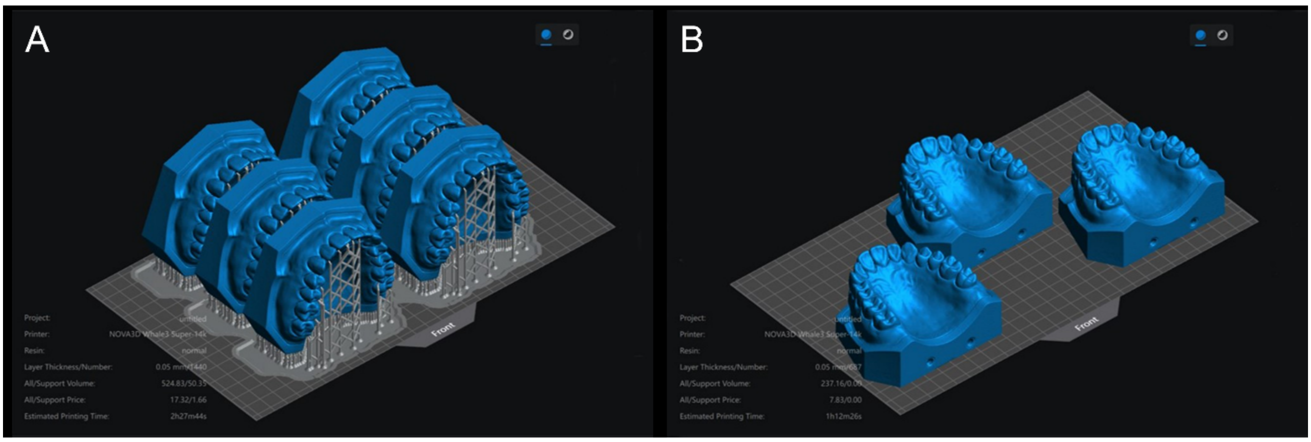

Figure 3. Variations in printing time with different printing orientations. (A) When the printing angle is set at (90°, 0°, 0°) and the layer thickness is 50 μm, the number of printed units is six, with a total printing time (T_{total}) of approximately 2 h, 27 min, and 44 s. (B) When the printing angle is set at (0°, 0°, 0°) and the layer thickness is 50 μm, the number of printed units is three, with a total printing time (T_{total}) of approximately 1 h, 12 min, and 26 s.

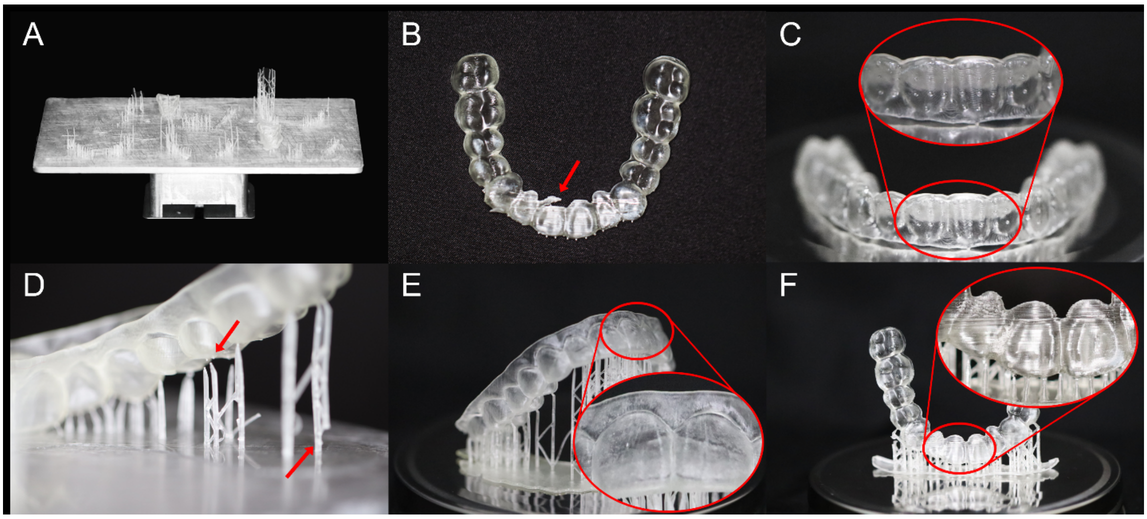

Figure 4. Common print quality problems. (A) Build plate adhesion failure: prints detach from the build plate or float in the resin. (B) Delamination: poor interlayer bonding leading to separation during printing. (C) Surface roughness: irregular surfaces with spots. (D) Support failure: broken, detached. (E) Dimensional inaccuracy: deviations in geometry due to resin residue. (F) Mechanical issues: defects caused by layer shifting or z-axis vibration.

Table 5. Common print quality problems and corresponding solutions

Problems	Description	Causes	Solutions
Build plate adhesion failure[53,106]	The print fails to stick to the build plate, floats in the resin, or detaches after a few layers	The build plate is not leveled	Re-level the build plate
		Inadequate bottom exposure	Increase bottom layer exposure time
		Contaminated build plate	Clean the build plate thoroughly
		Resin is too cold or too viscous	Maintain resin temperature at 20–28 °C
Delamination[53,107–109]	The print separates during printing; layers fail to bond with adjacent layers	Insufficient exposure of normal layers	Increase layer exposure time
		Lift speed too high	Reduce lift speed
		Inadequate or weak supports	Increase support density and diameter
		Large layer cross-section causing suction	Reorient model to minimize cross-sectional area per layer
Surface roughness[104,110]	Surface appears rough, with white spots, sticky texture, or holes	Overexposure or underexposure	Optimize exposure parameters
		Contaminated or settled resin	Filter and stir resin before use
		Inadequate cleaning	Clean thoroughly and dry completely
		Ambient light interference	Minimize ambient ultraviolet light exposure
Support failure[28,44]	Supports break, detach, are hard to remove, or leave deep marks	Supports are too thin or sparse	Increase support density and diameter
		Poor support placement	Manually optimize support placement
		Supports overly strong or weak	Use spherical support tips for easier removal and minimal damage
Dimensional inaccuracy[59,76]	The printed model does not match the intended dimensions; it may warp or shrink	Over- or under-exposure	Calibrate exposure time and use compensation settings
		Residual resin not fully cleaned	Ensure thorough post-cleaning
		Resin settling	Stir resin evenly before use
		Humidity fluctuations	Dry parts completely before post-curing
		Environmental temperature	Switch to resins with better thermal stability
Mechanical issues[106]	The model shows layer shifting, noise during printing, or z-axis (lifting axis) vibration	The z-axis is loose or contaminated	Clean and lubricate the z-axis screw
		Resin leakage into mechanical assemblies	Tighten or replace worn mechanical parts

4.4. Outlook

Recent studies suggest that dental DLP resins are evolving to achieve a balance between dimensional accuracy and mechanical strength. Low-shrinkage resins can improve dimensional accuracy in models, restorations, orthodontic appliances, and surgical guides[116], while filler-modified ceramic and glass-reinforced composites enhance fracture toughness without sacrificing adequate stiffness, supporting indication-specific material design for dental crowns.[117] These advances indicate that future parameter optimization in dental DLP will increasingly depend on resin chemistry tailored to clinical applications.

Given that dental DLP printing quality is influenced by multiple factors, trial-and-error optimization is often inefficient. Artificial intelligence and machine learning (ML), therefore, offer promising tools to improve efficiency, reproducibility, and precision. Recent studies have shown that ML can capture nonlinear parameter interactions to enhance printing fidelity, enabling fabrication of 20 μm-scale microchannels and triply periodic minimal surface microstructures with sub-2 μm error.[118] ML has also been applied to grayscale exposure optimization, deformation inverse design, and material–process–property mapping, highlighting its potential to address current challenges in dental DLP.[119–123]

Although dental DLP has already been adopted in many clinical settings, its industrial chain is still evolving and remains insufficiently mature in terms of standardized workflows, integrated industrial coordination, and large-scale clinical translation. At present, its commercialization relies on the coordinated contributions of multiple sectors across the industrial chain. Academic and clinical research institutions (e.g., West China Hospital of Stomatology; Peking University Hospital of Stomatology) serve as the primary source of innovation, driving advances in materials, algorithms, and processing strategies, and enabling translational validation (e.g., the Huaxi Intelligent Large Model). Dental device manufacturers (e.g., Angelalign; EA Medical Instruments) focus on productization and scalable fabrication of dental models and appliances.[124] Building on these developments, integrated digital solution providers (e.g., Shining 3D; SprintRay) facilitate clinical adoption by delivering end-to-end digital workflows that support chairside applications, such as intraoral scanning and the chairside fabrication of temporary restorations.[125,126] In parallel, industrial clusters (e.g., China Dental Valley) further promote ecosystem-level integration among academia, industry, and clinical practice.[127] In the future, further commercialization of dental DLP will depend on closer cross-sector coordination and the establishment of more standardized, scalable, and clinically validated production pathways.

5. Conclusion

Although 3D printing has demonstrated remarkable potential in dentistry, its outcomes remain highly dependent on multiple interacting factors, including printing orientation, support design, and post-curing conditions. Currently, there is a lack of standardized, product-specific protocols for clinical applications. Most DLP dental studies rely on idealized standard test pieces, with limited systematic evaluation of actual dental devices. Moreover, research often isolates single parameters and overlooks their interactions, while inconsistencies across different printing systems and research methods hinder comparability. Therefore, to enhance the reliability and clinical utility of printed devices, manufacturers are encouraged to provide detailed, material-specific parameter guidelines, while future studies should focus on developing standardized and evidence-based workflows tailored to different clinical scenarios.

This practice-oriented review highlights the critical role of printing parameters and post-processing details in DLP 3D printing for dental applications. By systematically analyzing printing orientation, support design, layer thickness, exposure time, and post-processing steps, recommended parameter ranges along with their respective advantages and limitations are proposed. These insights provide dentists and technicians with actionable protocols to improve the overall quality and printing efficiency of printed appliances, thereby enabling clinical large-scale implementation of DLP printing in personalized and chairside dentistry.

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Conflict of interest

The authors declare they have no competing interests.

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Ethics approval and consent to participate

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Consent for publication

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Further disclosure

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References

1. Ng WL, An J, Chua CK. Process, material, and regulatory considerations for 3D printed medical devices and tissue constructs. *Engineering*. 2024;36:146-166.

   doi: 10.1016/j.eng.2024.01.028

2. Chen J, Chen J, Wang H, *et al*. Fabrication and development of mechanical metamaterials via additive manufacturing for biomedical applications: A review. *Int J Extreme Manuf*. 2025;7(1):012001.

   doi: 10.1088/2631-7990/ad88e3

3. Wang X, Liu J, Zhang Y, *et al*. Advances in precision microfabrication through digital light processing: System development, material and applications. *Virtual Phys Prototyping*. 2023;18(1):e2248101.

   doi: 10.1080/17452759.2023.2248101

4. Chen Y, Wei J. Application of 3D printing technology in dentistry: A review. *Polymers*. 2025;17(7):886.

   doi: 10.3390/polym17070886

5. Liu Y, Sing SL, Lim RXE, Yeong WY, Goh BT. Preliminary investigation on the geometric accuracy of 3D printed dental implant using a monkey maxilla incisor model. *Int J Bioprint*. 2022;8(1):476.

   doi: 10.18063/ijb.v8i1.476

6. Pyo SW, Kim DJ, Han JS, Yeo ISL. Ceramic materials and technologies applied to digital works in implant-supported restorative dentistry. *Materials*. 2020;13(8):1964.

   doi: 10.3390/ma13081964

7. Zou R, Bi L, Huang Y, *et al*. A biocompatible silicon nitride dental implant material prepared by digital light processing technology. *J Mech Behav Biomed Mater*. 2023;141:105756.

   doi: 10.1016/j.jmbbm.2023.105756

8. Zhao W, Singh P, Han J, Shen F, Hu K, Tsoi JKH. Precision-optimized process control in DLP printing of ultra-thin zirconia prostheses: A multi-factor accuracy analysis. *Dent Mater*. 2025;41(12):1609-1619.

   doi: 10.1016/j.dental.2025.08.019

9. Pereira ABN, Almeida RC, Marassi C, Abdo Quintão CC, Carvalho FDAR. Do low-cost 3-dimensional printers produce suitable dental models? *Am J Orthod Dentofacial Orthop*. 2022;161(6):858-865.

   doi: 10.1016/j.ajodo.2021.06.018

10. Németh A, Vitai V, Czumbel ML, *et al*. Clear guidance to select the most accurate technologies for 3D printing dental models—A network meta-analysis☆. *J Dent*. 2023;134:104532.

    doi: 10.1016/j.jdent.2023.104532

11. Fortune Business Insights. Dental 3D printer market. Published 2025. Available from: https://www.fortunebusinessinsights.com/dental-3d-printer-market-110140 [Last accessed on November 18, 2025].

12. Dimitrova M, Vlahova A, Kalachev Y, Zlatev S, Kazakova R, Capodiferro S. Recent advances in 3D printing of polymers for application in prosthodontics. *Polymers*. 2023;15(23):4525.

    doi: 10.3390/polym15234525

13. Sun C, Fang N, Wu DM, Zhang X. Projection micro-stereolithography using digital micro-mirror dynamic mask. *Sens. Actuators A Phys*. 2005;121(1):113-120.

    doi: 10.1016/j.sna.2004.12.011

14. Chaudhary R, Fabbri P, Leoni E, Mazzanti F, Akbari R, Antonini C. Additive manufacturing by digital light processing: A review. *Prog Addit Manuf*. 2023;8(2):331-351.

    doi: 10.1007/s40964-022-00336-0

15. Divakaran N, Das JP, P v AK, Mohanty S, Ramadoss A, Nayak SK. Comprehensive review on various additive manufacturing techniques and its implementation in electronic devices. *J Manuf Syst*. 2022;62:477-502.

    doi: 10.1016/j.jmsy.2022.01.002

16. Tsolakis IA, Papaioannou W, Papadopoulou E, Dalampira M, Tsolakis AI. Comparison in terms of accuracy between DLP and LCD printing technology for dental model printing. *Dent J*. 2022;10(10):181.

doi: 10.3390/dj10100181

17. Park JM, Jeon J, Koak JY, Kim SK, Heo SJ. Dimensional accuracy and surface characteristics of 3D-printed dental casts. *J Prosthet Dent*. 2021;126(3):427-437.

    doi: 10.1016/j.prosdent.2020.07.008

18. Wu L, Zhao L, Jian M, Mao Y, Yu M, Guo X. EHMP-DLP: Multi-projector DLP with energy homogenization for large-size 3D printing. *Rapid Prototyping J*. 2018;24(9):1500-1510.

    doi: 10.1108/RPJ-04-2017-0060

19. Veligdan JT, Beiser L, Biscardi C, Brewster C, DeSanto L. Polyplanar optical display. In: Hopper DG, ed. *Cockpit Displays IV: Flat Panel Displays for Defense Applications*. SPIE; 1997; 3057:320-330.

    doi: 10.1117/12.277012

20. Quan H, Zhang T, Xu H, Luo S, Nie J, Zhu X. Photo-curing 3D printing technique and its challenges. *Bioact Mater*. 2020;5(1):110-115.

    doi: 10.1016/j.bioactmat.2019.12.003

21. Caussin E, Moussally C, Le Goff S, *et al*. Vat photopolymerization 3D printing in dentistry: A comprehensive review of actual popular technologies. *Materials*. 2024;17(4):950.

    doi: 10.3390/ma17040950

22. Kim SY, Shin YS, Jung HD, Hwang CJ, Baik HS, Cha JY. Precision and trueness of dental models manufactured with different 3-dimensional printing techniques. *Am J Orthod Dentofac Orthop*. 2018;153(1):144-153.

    doi: 10.1016/j.ajodo.2017.05.025

23. Piedra-Cascón W, Sadeghpour M, Att W, Revilla-León M. A vat-polymerized 3-dimensionally printed dual-material occlusal device: A dental technique. *J Prosthet Dent*. 2021;126(3):271-275.

    doi: 10.1016/j.prosdent.2020.07.011

24. Zhang J, Hu Q, Wang S, Tao J, Gou M. Digital Light Processing Based Three-dimensional Printing for Medical Applications. *Int J Bioprinting*. 2019;6(1):242.

    doi: 10.18063/ijb.v6i1.242

25. Mohan Pandey P, Venkata Reddy N, Dhande SG. Slicing procedures in layered manufacturing: A review. *Rapid Prototyping J*. 2003;9(5):274-288.

    doi: 10.1108/13552540310502185

26. Piedra-Cascón W, Krishnamurthy VR, Att W, Revilla-León M. 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: A narrative review. *J Dent*. 2021;109:103630.

    doi: 10.1016/j.jdent.2021.103630

27. Jin MC, Yoon HI, Yeo IS, Kim SH, Han JS. The effect of build angle on the tissue surface adaptation of maxillary and mandibular complete denture bases manufactured by digital light processing. *J Prosthet Dent*. 2020;123(3):473-482.

    doi: 10.1016/j.prosdent.2018.12.014

28. Jiang J, Xu X, Stringer J. Support structures for additive manufacturing: A review. *J Manuf Mater Process*. 2018;2(4):64.

    doi: 10.3390/jmmp2040064

29. Cheng W, Fuh JYH, Nee AYC, Wong YS, Loh HT, Miyazawa T. Multi-objective optimization of part- building orientation in stereolithography. *Rapid Prototyp J*. 1995;1(4):12-23.

    doi: 10.1108/13552549510104429

30. CHITUBOX. A complete guide about adding supports in SLA/DLP/LCD 3D printing. *CHITUBOX Docs*. Available from: https://docs.chitubox.com/en-US/academy/a-complete-guide-about-adding-supports-in-sladlplcd-3d-printing [Last accessed on May 6, 2025].

31. Wang Z, Zhang Y, Tan S, Ding L, Bernard A. Support point determination for support structure design in additive manufacturing. *Addit Manuf*. 2021;47:102341.

    doi: 10.1016/j.addma.2021.102341

32. Shen M, Zhao W, Xing B, *et al*. Effects of exposure time and printing angle on the curing characteristics and flexural strength of ceramic samples fabricated via digital light processing. *Ceram Int*. 2020;46(15):24379-24384.

    doi: 10.1016/j.ceramint.2020.06.220

33. Zhang ZC, Li PL, Chu FT, Shen G. Influence of the three-dimensional printing technique and printing layer thickness on model accuracy. *J Orofac Orthop*. 2019;80(4):194-204.

    doi: 10.1007/s00056-019-00180-y

34. Taormina G, Sciancalepore C, Messori M, Bondioli F. 3D printing processes for photocurable polymeric materials: Technologies, materials, and future trends. *J Appl Biomater Funct Mater*. 2018;16(3):151-160.

    doi: 10.1177/2280800018764770

35. Hwangbo NK, Nam NE, Choi JH, Kim JE. Effects of the washing time and washing solution on the biocompatibility and mechanical properties of 3D printed dental resin materials. *Polymers*. 2021;13(24):4410.

    doi: 10.3390/polym13244410

36. Li P, Lambart AL, Stawarczyk B, Reymus M, Spintzyk S. Postpolymerization of a 3D-printed denture base polymer: Impact of post-curing methods on surface characteristics, flexural strength, and cytotoxicity. *J Dent*. 2021;115:103856.

    doi: 10.1016/j.jdent.2021.103856

37. Par M, Gamulin O, Marovic D, Klaric E, Tarle Z. Effect of temperature on post-cure polymerization of bulk-fill composites. *J Dent*. 2014;42(10):1255-1260.

doi: 10.1016/j.jdent.2014.08.004

38. Reymus M, Fabritius R, Keßler A, Hickel R, Edelhoff D, Stawarczyk B. Fracture load of 3D-printed fixed dental prostheses compared with milled and conventionally fabricated ones: the impact of resin material, build direction, post-curing, and artificial aging—an in vitro study. *Clin Oral Investig*. 2020;24(2):701-710.

    doi: 10.1007/s00784-019-02952-7

39. Wada J, Wada K, Garoushi S, *et al*. Effect of 3D printing system and post-curing atmosphere on micro- and nano-wear of additive-manufactured occlusal splint materials. *J Mech Behav Biomed Mater*. 2023;142:105799.

    doi: 10.1016/j.jmbbm.2023.105799

40. Hassanpour M, Narongdej P, Alterman N, Moghtadernejad S, Barjasteh E. Effects of post-processing parameters on 3D-printed dental appliances: A review. *Polymers*. 2024;16(19):2795.

    doi: 10.3390/polym16192795

41. Rudolph H, Ostertag S, Ostertag M, Walter MH, Luthardt RG, Kuhn K. Reliability of light microscopy and a computer-assisted replica measurement technique for evaluating the fit of dental copings. *J Appl Oral Sci*. 2018;26(0).

    doi: 10.1590/1678-7757-2016-0590

42. Hmood AN, Ebaya MMA, El-Embaby AES. The in vitro effect of electronic versus conventional cigarettes on color stability and surface roughness of dental resin composites. *Sci Rep*. 2025;15(1):42927.

    doi: 10.1038/s41598-025-28238-5

43. Yıldırım Ö, Yeşil Z, Hatipoğlu Ö. Effect of different 3D-printing systems on the flexural strength of provisional fixed dental prostheses: A systematic review and network meta-analysis of in vitro studies. *BMC Oral Health*. 2025;25(1):82.

    doi: 10.1186/s12903-025-05470-z

44. Namano S, Kanazawa M, Katheng A, *et al*. Effect of support structures on the trueness and precision of 3D printing dentures: An *in vitro* study. *J Prosthodont Res*. 2024;68(1):114-121.

    doi: 10.2186/jpr.JPR_D_22_00266

45. Alshamrani AA, Raju R, Ellakwa A. Effect of printing layer thickness and postprinting conditions on the flexural strength and hardness of a 3D-printed resin. *Biomed Res Int*. 2022;2022(1):8353137.

    doi: 10.1155/2022/8353137

46. Kouhi M, de Souza Araújo IJ, Asa'ad F, *et al*. Recent advances in additive manufacturing of patient-specific devices for dental and maxillofacial rehabilitation. *Dent Mater*. 2024;40(4):700-715.

    doi:10.1016/j.dental.2024.02.006

47. Campi F, Favi C, Germani M, Mandolini M. CAD-integrated design for manufacturing and assembly in mechanical design. *Int J Comput Integr Manuf*. 2022;35(3):282-325.

    doi: 10.1080/0951192X.2021.1992659

48. Umaras E, Barari A, Horikawa O, Tsuzuki MSG. Dimensional tolerances in mechanical assemblies: a cost-based optimization approach. *Appl Sci*. 2023;13(16):9202.

    doi: 10.3390/app13169202

49. Dai J, Li P, Spintzyk S, Liu C, Xu S. Influence of additive manufacturing method and build angle on the accuracy of 3D-printed palatal plates. *J Dent*. 2023;132:104449.

    doi: 10.1016/j.jdent.2023.104449

50. Su J, Mo Y, Shangguan P, Panwisawas C, Jiang F, Sing SL. Additive manufacturing-by-design for support structures: A critical review. *Int J Extreme Manuf*. 2025;7(5):052002.

    doi: 10.1088/2631-7990/add4d2

51. Gaviolli E, Collares FM, Balbinot GDS, Leitune VCB. Optimizing photoinitiator concentration in 3D-printed resins for provisional dental restorations. *Braz Dent J*. 2025;36:e25-6567.

    doi: 10.1590/0103-644020256567

52. Kirby S, Pesun I, Nowakowski A, França R. Effect of Different Post-Curing Methods on the Degree of Conversion of 3D-Printed Resin for Models in Dentistry. *Polymers*. 2024;16(4):549.

    doi: 10.3390/polym16040549

53. Wu D, Zhao Z, Zhang Q, Qi HJ, Fang D. Mechanics of shape distortion of DLP 3D printed structures during UV post-curing. *Soft Matter*. 2019;15(30):6151-6159.

    doi: 10.1039/C9SM00725C

54. Ng WL, Paula CTB, Serra AC, Coelho JFJ, Bartolo P. Vat photopolymerization-based bioprinting: Shaping next-generation tissues with light. *Interdiscip Med*. 2026;4(1):e70078.

    doi: 10.1002/inmd.70078

55. Telatar BC, Telatar GY. A comparative in vitro study on monomer release from flash-free or conventional bonding systems. *Clin Oral Investig*. 2025;29(3):169.

    doi: 10.1007/s00784-025-06250-3

56. Gaviolli E, Collares FM, Balbinot GDS, Özcan M, Leitune VCB. Effect of adding ytterbium trifluoride filler particles on the mechanical, physicochemical and biological properties of methacrylate-based experimental resins for 3D printing. *Dent Mater*. 2024;40(10):1685-1691.

    doi: 10.1016/j.dental.2024.07.023

57. Bertolo MVL, Moraes RDCM, Pfeifer C, Salgado VE, Correr ARC, Schneider LFJ. Influence of photoinitiator system on physical-chemical properties of experimental self-adhesive

composites. *Braz Dent J*. 2017;28(1):35-39.

doi: 10.1590/0103-6440201700841

58. Schönl F, Demleitner M, Angermann J, *et al*. Synthesis and evaluation of novel urethane macromonomers for the formulation of fracture tough 3D printable dental materials. *J Mech Behav Biomed Mater*. 2024;160:106737.

doi: 10.1016/j.jmbbm.2024.106737

59. Osman R, Alharbi N, Wismeijer D. Build Angle: Does It Influence the Accuracy of 3D-Printed Dental Restorations Using Digital Light-Processing Technology? *Int J Prosthodont*. 2017;30(2):182-188.

doi: 10.11607/ijp.5117

60. Ryu JE, Kim YL, Kong HJ, Chang HS, Jung JH. Marginal and internal fit of 3D printed provisional crowns according to build directions. *J Adv Prosthodont*. 2020;12(4):225.

doi: 10.4047/jap.2020.12.4.225

61. Park GS, Kim SK, Heo SJ, Koak JY, Seo DG. Effects of Printing Parameters on the Fit of Implant-Supported 3D Printing Resin Prosthetics. *Materials*. 2019;12(16):2533.

doi: 10.3390/ma12162533

62. Alkhateeb RI, Algaoud HS, Aldamanhori RB, Alshubaili RR, Alalawi H, Gad MM. Fracture Load of 3D-Printed Interim Three-Unit Fixed Dental Prostheses: Impact of Printing Orientation and Post-Curing Time. *Polymers*. 2023;15(7):1737.

doi: 10.3390/polym15071737

63. Song S, Zhang J, Liu M, Li F, Bai S. Effect of build orientation and layer thickness on manufacturing accuracy, printing time, and material consumption of 3D printed complete denture bases. *J Dent*. 2023;130:104435.

doi: 10.1016/j.jdent.2023.104435

64. Hussein MO, Hussein LA. Trueness of 3D printed partial denture frameworks: build orientations and support structure density parameters. *J Adv Prosthodont*. 2022;14(3):150.

doi: 10.4047/jap.2022.14.3.150

65. Chaiamornsup P, Iwasaki N, Tsuchida Y, Takahashi H. Effects of build orientation on adaptation of casting patterns for three-unit partial fixed dental prostheses fabricated by using digital light projection. *J Prosthet Dent*. 2022;128(5):1047-1054.

doi: 10.1016/j.prosdent.2021.01.006

66. Hussein MO, Hussein LA. Optimization of Digital Light Processing Three-Dimensional Printing of the Removable Partial Denture Frameworks; The Role of Build Angle and Support Structure Diameter. *Materials*. 2022;15(6):2316.

doi: 10.3390/ma15062316

67. Ko J, Bloomstein RD, Briss D, *et al*. Effect of build angle and layer height on the accuracy of 3-dimensional printed dental models. *Am. J. Orthod. Dentofacial Orthop*. 2021;160(3):451-458.e2.

doi: 10.1016/j.ajodo.2020.11.039

68. Tahir N, Abduo J. An In Vitro Evaluation of the Effect of 3D Printing Orientation on the Accuracy of Implant Surgical Templates Fabricated By Desktop Printer. *J Prosthodont*. 2022;31(9):791-798.

doi: 10.1111/jopr.13485

69. Boyer RA, Kasper FK, English JD, Jacob HB. Effect of print orientation on the dimensional accuracy of orthodontic aligners printed 3-dimensionally. *Am J Orthod Dentofacial Orthop*. 2021;160(5):732-742.e1.

doi: 10.1016/j.ajodo.2021.01.018

70. Süpple J, Von Glasenapp J, Hofmann E, Jost-Brinkmann PG, Koch PJ. Accurate Bracket Placement with an Indirect Bonding Method Using Digitally Designed Transfer Models Printed in Different Orientations—An In Vitro Study. *J Clin Med*. 2021;10(9):2002.

doi: 10.3390/jcm10092002

71. Saadat Sarmadi B, Schmidt F, Beuer F, *et al*. The effect of build angle and artificial aging on the accuracy of SLA- and DLP-printed occlusal devices. *Polymers*. 2024;16(12):1714.

doi: 10.3390/polym16121714

72. Cao L, Tian L, Peng H, Zhou Y, Lu L. Constrained stacking in DLP 3D printing. *Comput Graphics*. 2021;95:60-68.

doi: 10.1016/j.cag.2021.01.003

73. Farkas AZ, Galatanu SV, Nagib R. The Influence of Printing Layer Thickness and Orientation on the Mechanical Properties of DLP 3D-Printed Dental Resin. *Polymers*. 2023;15(5):1113.

doi: 10.3390/polym15051113

74. Cheadle AMG, Maier E, Palin WM, Tomson PL, Poologasundarampillai G, Hadis MA. The impact of modifying 3D printing parameters on mechanical strength and physical properties in vat photopolymerisation. *Sci Rep*. 2025;15(1):12592.

doi: 10.1038/s41598-025-97294-8

75. Cameron AB, Tong K, Tadakamadla S, Evans JL, Abuzar M. Effect of build orientation on the trueness of occlusal splints fabricated by three-dimensional printing. *J Oral Sci*. 2023;65(4):261-264.

doi: 10.2334/josnusd.23-0115

76. de Castro EF, Nima G, Rueggeberg FA, Giannini M. Effect of build orientation in accuracy, flexural modulus, flexural strength, and microhardness of 3D-printed resins for provisional restorations. *J Mech Behav Biomed Mater*. 2022;136:105479.

doi: 10.1016/j.jmbbm.2022.105479

77. Jafarpour D, El-Amier N, Tahboub K, Zimmermann E, Pero AC, de Souza R. Effects of DLP printing orientation and postprocessing regimes on the properties of 3D printed denture bases. *J Prosthet Dent*. 2025;134(1):239.e1-239.e9.

doi: 10.1016/j.prosdent.2025.02.035

78. Mudhaffer S, Haider J, Satterthwaite J, Silikas N. Effects of print orientation and artificial aging on the flexural strength and flexural modulus of 3D printed restorative resin materials. *J Prosthet Dent*. 2025;133(5):1345-1357.

doi: 10.1016/j.prosdent.2024.08.008

79. Wang D, Shen Z, Fang Q, *et al*. Steady conformal support structures for 3D printing. In: *2024 IEEE 20th International Conference on Automation Science and Engineering (CASE)*. IEEE;2024:2243-2248.

doi: 10.1109/CASE59546.2024.10711341

80. Alexander P, Allen S, Dutta D. Part orientation and build cost determination in layered manufacturing. *Comput-Aided Des*. 1998;30(5):343-356.

doi: 10.1016/S0010-4485(97)00083-3

81. Paul R, Anand S. Optimization of layered manufacturing process for reducing form errors with minimal support structures. *J Manuf Syst*. 2015;36:231-243.

doi: 10.1016/j.jmsy.2014.06.014

82. Homire C. Graphy Tera Harz flexible base: printed partial denture review. Institute of Digital Dentistry. Published 2023. Available from: https://instituteofdigitaldentistry.com/3d-printing/graphy-tera-herz-flexible-base-resin-printed-partial-denture-review/ [Last accessed on May 6, 2025].

83. Prevest DenPro Ltd. 3D printing dental resins: printing specifications [technical datasheet]. Published 2023. Available from: https://www.prevestdenpro.com/wp-content/uploads/2023/07/3D-Printing-Dental-Resins-Printing-Specifications.pdf [Last accessed on May 6, 2025].

84. Lee WJ, Jo YH, Yilmaz B, Yoon HI. Effect of build angle, resin layer thickness and viscosity on the surface properties and microbial adhesion of denture bases manufactured using digital light processing. *J Dent*. 2023;137:104608.

doi: 10.1016/j.jdent.2023.104608

85. Billerbeck K, Hägele C, Träger J. Relation of the working curve and exposure intensity in VPP 3D-printing. *Prog Addit Manuf*. 2024;9(4):1015-1023.

doi: 10.1007/s40964-023-00498-5

86. Sasany R, Jamjoon FZ, Kendirci MY, Yilmaz B. Effect of printing layer thickness on optical properties and surface roughness of 3D-printed resins: An in vitro study. *Int J Prosthodont*. 2024;37(7):165-173.

doi: 10.11607/ijp.8965

87. Nelaturi S, Behandish M, Mirzendehdel AM, De Kleer J. Automatic support removal for additive manufacturing post processing. *Comput-Aided Des*. 2019;115:135-146.

doi: 10.1016/j.cad.2019.05.030

88. Mayer J, Stawarczyk B, Vogt K, Hickel R, Edelhoff D, Reymus M. Influence of cleaning methods after 3D printing on two-body wear and fracture load of resin-based temporary crown and bridge material. *Clin Oral Investig*. 2021;25(10):5987-5996.

doi: 10.1007/s00784-021-03905-9

89. Jang W, Kook GS, Kang JH, *et al*. Effect of Washing Condition on the Fracture Strength, and the Degree of Conversion of 3D Printing Resin. *Appl Sci*. 2021;11(24):11676.

doi: 10.3390/app112411676

90. Xu Y, Xepapadeas AB, Koos B, Geis-Gerstorfer J, Li P, Spintzyk S. Effect of post-rinsing time on the mechanical strength and cytotoxicity of a 3D printed orthodontic splint material. *Dent Mater*. 2021;37(5):e314-e327.

doi: 10.1016/j.dental.2021.01.016

91. Lambart AL, Xepapadeas AB, Koos B, Li P, Spintzyk S. Rinsing postprocessing procedure of a 3D-printed orthodontic appliance material: Impact of alternative post-rinsing solutions on the roughness, flexural strength and cytotoxicity. *Dent Mater*. 2022;38(8):1344-1353.

doi: 10.1016/j.dental.2022.06.010

92. Scherer MD, Al-Haj Husain N, Barmak AB, Kois JC, Özcan M, Revilla-León M. Influence of postprocessing rinsing solutions and duration on flexural strength of aged and nonaged additively manufactured interim dental material. *J Prosthet Dent*. 2024;131(5):959-968.

doi: 10.1016/j.prosdent.2022.03.034

93. Jindal P, Juneja M, Bajaj D, Siena FL, Breedon P. Effects of post-curing conditions on mechanical properties of 3D printed clear dental aligners. *Rapid Prototyp J*. 2020;26(8):1337-1344.

doi: 10.1108/RPJ-04-2019-0118

94. Özden Y, Altınok Uygun L. Effects of postcuring times on the trueness of 3D -printed dental inlays made with permanent resins. *Clin Oral Investig*. 2025;29(5):244.

doi: 10.1007/s00784-025-06319-z

95. Sahrir CD, Lin W, Wang C, Lin W. Effects of post-curing light intensity on the trueness, compressive strength, and resin polymerization characteristics of 3D-printed 3-unit fixed dental prostheses. *J Prosthodont*. 2024.

doi: 10.1111/jopr.13951

96. Manoukakis T, Nikolaidis AK, Koulaouzidou EA. Polymerization kinetics of 3D-printed orthodontic aligners under different UV post-curing conditions. *Prog Orthod*. 2024;25(1):42.

doi: 10.1186/s40510-024-00540-4

97. Perea-Lowery L, Gibreel M, Vallittu PK, Lassila LV. 3D-printed vs. Heat-polymerizing and autopolymerizing denture base acrylic resins. *Materials*. 2021;14(19):5781.

doi: 10.3390/ma14195781

98. Finck NS, Fraga MAA, Correr AB, *et al*. Comparative evaluation of mechanical and thermal properties of 3D-printed restorative polymers: Effects of resin type, printer technology, and post-curing time. *J Mech Behav Biomed Mater*. 2025;172:107166.

doi: 10.1016/j.jmbbm.2025.107166

99. Topsakal KG, Aksoy M, Süküt Y, Duran GS. Effect of post-curing parameters and material thickness on the color stability of 3D-printed dental resins: An in vitro study. *Int Orthod*. 2025;23(2):100985.

doi: 10.1016/j.ortho.2025.100985

100. Bouchema TSE, Saunier J, Mollier L, Mauriello J, Savard B, Yagoubi N. Comparison of three dental resins for 3D printing of orthodontic appliances: Comparison of leaching, biocompatibility, and thermo-mechanical properties after post-curing and aging. *Dent Mater*. 2026;42(3):381-402.

doi: 10.1016/j.dental.2025.10.013

101. Sahrir CD, Ruslin M, Lee SY, Lin WC. Effect of various post-curing light intensities, times, and energy levels on the color of 3D-printed resin crowns. *J Dent Sci*. 2024;19(1):357-363.

doi: 10.1016/j.jds.2023.07.008

102. Nowacki B, Kowol P, Kozioł M, Olesik P, Wieczorek J, Wacławiak K. Effect of post-process curing and washing time on mechanical properties of mSLA printouts. *Materials*. 2021;14(17):4856.

doi: 10.3390/ma14174856

103. Morita K, Tsuka H, Kato K, Tsuga K. Effect of polymerization temperature on the properties of autopolymerizing resin. *J Prosthet Dent*. 2018;119(5):840-844.

doi: 10.1016/j.prosdent.2017.07.022

104. Kumbhar NN, Mulay AV. Post processing methods used to improve surface finish of products which are manufactured by additive manufacturing technologies: A review. *J Inst Eng India Ser C*. 2018;99(4):481-487.

doi: 10.1007/s40032-016-0340-z

105. Purple Dance. Dental LCD/DLP/SLA 3D printing post-processing. Purple Dance. Published 2023. Available from: https://purpledance.net/zh/blogs/news/dental-lcd-dlp-sla-3d-printing-post-processing [Last accessed on July 6, 2025].

106. Darulis A. Resin 3D printing troubleshooting: a comprehensive guide. AmeraLabs. Published 2023. Available from: https://ameralabs.com/blog/resin-3d-printing-troubleshooting/ [Last accessed on July 6, 2025].

107. Shan Y, Krishnakumar A, Qin Z, Mao H. Reducing lateral stair-stepping defects in liquid crystal display-based vat photopolymerization by defocusing the image pattern. *Addit Manuf*. 2022;52:102653.

doi: 10.1016/j.addma.2022.102653

108. Gojzewski H, Guo Z, Grzelachowska W, *et al*. Layer-by-Layer Printing of Photopolymers in 3D: How Weak is the Interface? *ACS Appl Mater Interfaces*. 2020;12(7):8908-8914.

doi: 10.1021/acsami.9b22272

109. Phrozen3D. Avoid common 3D printing mistakes: essential tips for resin 3D printer beginners. Phrozen3D. Published 2024. Available from: https://phrozen3d.com/en/blogs/tutorials/3d-printing-mistakes-to-avoid-for-beginners [Last accessed on April 15, 2026].

110. Pan Y, Zhao X, Zhou C, Chen Y. Smooth surface fabrication in mask projection based stereolithography. *J Manuf Processes*. 2012;14(4):460-470.

doi: 10.1016/j.jmapro.2012.09.003

111. Narongdej P, Hassanpour M, Alterman N, Rawlins-Buchanan F, Barjasteh E. Advancements in clear aligner fabrication: A comprehensive review of direct-3D printing technologies. *Polymers*. 2024;16(3):371.

doi: 10.3390/polym16030371

112. Tang XM, Na-Yu, Bai BD, Peng-Wang, Lu-Liu, Tan FB. Effect of build position on the accuracy and flexural properties of resin model materials for three-dimensional printing technologies. *J Indian Prosthodont Soc*. 2026;26(1):32-42.

doi: 10.4103/jips.jips_106_25

113. Dixit CK, Kadimisetty K, Rusling J. 3D-printed miniaturized fluidic tools in chemistry and biology. *TrAC, Trends Anal Chem*. 2018;106:37-52.

doi: 10.1016/j.trac.2018.06.013

114. U.S. Food and Drug Administration. General principles of software validation: final guidance for industry and FDA staff. Published 2002. Available from: https://www.fda.gov/media/73141/download [Last accessed on April 15, 2026].

115. U.S. Food and Drug Administration. Technical considerations for additive manufactured medical devices. Published 2020. Available from: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/technical-considerations-additive-manufactured-medical-devices[Last accessed on April 5, 2026].

116. Ling L, Taremi N, Malyala R. A novel low-shrinkage resin for 3D printing. *J Dent*. 2022;118:103957.

doi: 10.1016/j.jdent.2022.103957

117. Orgev A, Cakmak G, Marques V, Yilmaz B, Li R. The effect of crown material type on the fracture strength of CAD-CAM fabricated crowns. *J Prosthet Dent*. 2026;135(3):578.E1-578.E6.

doi: 10.1016/j.prosdent.2025.10.020

118. Wang X, Liu J, Dong R, Gilchrist MD, Zhang N. High-precision digital light processing (DLP) printing of microstructures for microfluidics applications based on a machine learning approach. *Virtual Phys Prototyp*. 2024;19(1):e2318774.

doi: 10.1080/17452759.2024.2318774

119. Poltue T, Montgomery SM, Sun X, *et al*. Machine learning-based optimization of pixel light intensities for improving polymerization accuracy in digital light processing 3D printing. *Adv Mater Technol*. 2025;10(20):e00902.

doi: 10.1002/admt.202500902

120. Maleki H, Asadi P, Akbari M, Peyghami M, Salarvand V, Bedir F. Incorporation of machine learning in the design of bio-nanocomposites produced by DLP 3D printer. *Results Eng*. 2025;27:105756.

doi: 10.1016/j.rineng.2025.105756

121. He H, Yang Y, Pan Y. Machine learning for continuous liquid interface production: Printing speed modelling. *J Manuf Syst*. 2019;50:236-246.

doi: 10.1016/j.jmsy.2019.01.004

122. Guan J, You S, Xiang Y, *et al*. Compensating the cell-induced light scattering effect in light-based bioprinting using deep learning. *Biofabrication*. 2022;14(1):015011.

doi: 10.1088/1758-5090/ac3b92

123. Zhao B, Zhang M, Dong L, Wang D. Design of grayscale digital light processing 3D printing block by machine learning and evolutionary algorithm. *Compos Commun*. 2022;36:101395.

doi: 10.1016/j.coco.2022.101395

124. Xie J, Zheng Y, Wu J. Three-dimensional dentoskeletal effects of the Angelalign A6 clear aligners in a skeletal class II growing patient: a case report. *Int Orthod*. 2023;21(2):100756.

doi: 10.1016/j.ortho.2023.100756

125. Shining 3D Tech. About SHINING 3D. Available from: https://www.shining3d.com/about-us [Last accessed on April 12, 2026].

126. SprintRay Inc. About SprintRay Inc. Available from: https://sprintray.com/company/ [Last accessed on April 12, 2026].

127. Sichuan Liangang Bonded Service. Starting with the "Ziyang plan," China Dental Valley creates a new blueprint for the integration of oral health "cause + industry." Available from: https://www.dentval.com/starting-with-the-ziyang-plan-china-dental-valley-creates-a-new-blueprint-for-the-integration-of-oral-health-cause--industry [Last accessed on April 15, 2026].