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Beyond Initial Accuracy: Long-Term Aging and Clinical Stability of 3D-Printed Dental Resins in the Oral Environment

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Abstract

Occlusal devices, denture bases, and definitive restorations intended for long-term intraoral use are increasingly produced by three-dimensional (3D) printing, yet evidence for the durability of 3D-printed dental resins comes mostly from in vitro testing and short-term clinical follow-up. In the mouth, saliva, thermal variation, cyclic loading, chemical agents, and biofilm act concurrently over time, so initial accuracy and strength do not guarantee long-term clinical stability. This narrative review examines the long-term aging and clinical stability of 3D-printed dental resins by considering the chemical, physical, biological, and mechanical factors inherent to the oral environment and how material composition, printing parameters, post-processing, and clinical exposure influence long-term performance. The reviewed evidence indicates that aging is material-specific and multifactorial, affecting mechanical, physical, and esthetic properties depending on the formulation, manufacturing protocol, and patient-related conditions. Laboratory aging provides important insight into durability, but methodological heterogeneity and the incomplete simulation of the combined oral environment limit prediction of long-term clinical behavior. This review argues that the long-term success of 3D-printed dental resins should be judged not by their properties immediately after fabrication but by their ability to maintain structural, mechanical, dimensional, esthetic, and biological stability under the combined challenges of the oral cavity. Standardized multifactorial aging protocols and adequately powered longitudinal clinical studies are needed before recommending these materials for routine long-term use.

Categories: Therapeutics, Medical Education, Dentistry
Keywords: 3d printing, additive manufacturing, aging, definitive restoration, dental resins, denture base, durability, occlusal splint, oral environment, polymer degradation

Introduction And Background

Over the past decade, three-dimensional (3D) printing, or additive manufacturing, has moved from a prototyping method to a mainstream dental technique, propelled by vat-polymerization technologies such as stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD) printing [1-2]. These technologies are now used across a wide range of restorative and prosthodontic applications, including surgical guides, occlusal splints, temporary and definitive crowns, complete and removable partial denture bases, orthodontic appliances, and fixed partial prostheses [1,3-4]. Although recent meta-analytic evidence confirms the high initial dimensional accuracy of 3D-printed resin appliances, including customized orthodontic brackets [5], initial bench accuracy does not guarantee intraoral longevity. Growing confidence in the mechanical and esthetic properties of these materials has led to their reformulation and marketing for both temporary and permanent restorative applications [6]. This shift has been facilitated by workflow advantages, including reduced material consumption, shorter chair time, and improved reproducibility compared with subtractive manufacturing or conventional fabrication methods [2,4]. Printable dental resins polymerize through light-activated conversion of liquid methacrylate monomers into a cross-linked network, and the proportion converted (the degree of conversion), together with cross-link density, largely determines mechanical strength, dimensional stability, and how much unreacted monomer remains available to leach; these concepts underlie the aging behavior discussed throughout.

However, the clinical presence of printed resins in the mouth has outpaced evidence of their durability. Available data largely describe immediate post-fabrication behavior and come from standardized dry, static, short-duration loading tests [7-8]. One study of a printed occlusal splint resin found that flexural strength and microhardness improved with build orientation and post-curing time but cautioned that cyclic fatigue, humidity, enzymatic degradation, and occlusal dynamics may be detrimental over time and can only be confirmed through randomized clinical trials [7]. A scoping review of 934 dental 3D-printing studies similarly found few clinical trials across most disciplines. It concluded that laboratory and animal data do not predict clinical success. Narrative reviews across specialties identify the lack of long-term clinical

follow-up, rather than any single material limitation, as the principal barrier to using printed resins for permanent indications [1,9]. Even studies reporting short-term clinical outcomes, such as a three-month follow-up of printed occlusal splints for temporomandibular disorders, are too brief to establish durability [10].

This gap matters because the oral cavity is not a passive environment: a printed resin is simultaneously exposed to water, cyclic loading, temperature fluctuation, chemical challenge from diet and hygiene products, and microbial colonization, all acting together rather than in isolation. Individual studies show variability in outcomes under these conditions. After thermocycling, water sorption and solubility are higher for 3D-printed denture base resins than for heat-polymerized resins [11]; after three months of aging in artificial saliva, water sorption rises significantly although flexural strength may remain competitive [12]; and other work reports that printed resins can show lower water sorption than heat-cured resin yet higher or lower solubility than conventional or milled resin depending on the aging protocol [13]. Initial dimensional accuracy or mechanical strength therefore does not guarantee long-term clinical reliability. This review asks the central question: does a 3D-printed dental resin that performs well immediately after printing remain stable after months or years of intraoral mechanical, thermal, chemical, and biological challenge? Answering it requires attention to the aging mechanisms themselves, not bench accuracy alone.

Review

Methodology

This structured narrative review was conducted in accordance with the Scale for the Assessment of Narrative Review Articles (SANRA) rather than as a systematic review. We searched PubMed, Scopus, Google Scholar, and ScienceDirect for English-language articles published from November 2021 through the final search date in 2026. November 2021 was selected as the starting point to capture approximately five years of recent evidence, given the rapid reformulation of printable dental resins and the emergence of materials marketed for definitive use. The search combined terms for additive manufacturing with terms for material and clinical outcomes, for example: ("3D printing" OR "additive manufacturing" OR "stereolithography" OR "digital light processing" OR "liquid crystal display") AND (resin OR "denture base" OR "occlusal splint" OR crown OR "fixed dental prosthesis" OR aligner) AND (aging OR thermocycling OR "water sorption" OR "degree of conversion" OR "post-curing" OR biofilm OR fatigue OR durability). Eligible records were systematic reviews and meta-analyses, in vitro and laboratory studies, and clinical and observational investigations addressing the composition, manufacturing variables, aging behavior, or clinical performance of 3D-printed dental resins. Records were excluded if they addressed metals or ceramics without a resin comparator, concerned 3D-printing applications unrelated to intraoral devices, were conference abstracts or non-English reports, or lacked an aging or durability outcome. Two authors screened records by title and abstract, assessed full texts against these criteria, resolved disagreements through discussion, and hand-searched the reference lists of retrieved articles. Consistent with the narrative review design, no formal risk-of-bias assessment or quantitative synthesis was performed, and no PRISMA flow diagram was prepared. These methodological limitations are acknowledged, and material-specific findings are distinguished from generalized conclusions throughout.

Oral environment as an aging system: mechanisms of resin degradation

The oral cavity is a demanding environment for 3D-printed polymers, which are exposed to several degradation factors acting at once: water and saliva, thermal fluctuation, mechanical load, chemical exposure and pH change, and microbial colonization [14-15]. Aging should therefore be understood not as a single process but as concurrent biological, chemical, physical, and mechanical actions that together affect biocompatibility, strength, esthetics, and dimensional stability [16-18]. Table *1* summarizes these stressors and their principal effects.

Oral stressor	Principal mechanism	Main effects on printed resin	Source
Water and saliva	Water sorption; enzymatic and hydrolytic action	Swelling, plasticization; reduced strength and dimensional stability	[11,12,19]
Thermal fluctuation	Repeated expansion and contraction	Internal stress, microcracking, color and surface change	[20-23]
Chemical and dietary exposure	Pigment uptake; exposure to alcohol, bleaching agents, and acids	Increased roughness and discoloration; reduced hardness	[24-26]
Mechanical loading	Cyclic, multidirectional occlusal and parafunctional forces	Fatigue, wear, deformation, crack propagation, fracture	[27,28]
Microbial biofilm	Pellicle formation, colonization, acid production	Lower local pH, surface degradation, reduced strength and reliability	[15,29-32]

TABLE 1: Oral cavity as a multifactorial aging system for 3D-printed dental resins

These stressors act concurrently rather than in isolation, a feature that laboratory protocols only partially reproduce.

3D: three-dimensional

Water and saliva constitute the aqueous environment in which printed dental materials function. In addition to water, saliva contains proteins, enzymes, and electrolytes that may contribute to material aging. Continuous water sorption causes swelling and plasticization of the polymer network, potentially compromising mechanical performance, physical stability, and esthetic properties [11-12,19]. Temperature fluctuations arise from body temperature and the consumption of hot and cold foods and beverages. These fluctuations cause expansion and contraction of the polymer matrix, potentially compromising dimensional stability and promoting microcrack formation and propagation that may ultimately lead to fracture [20-23]. Chemical exposure adds a further burden: dietary components, pigmented beverages such as tea and coffee, alcohol-containing or bleaching hygiene products, and medications increase surface roughness and discoloration and reduce strength and hardness [24-26].

Mechanically, occlusal forces during mastication apply cyclic, repetitive, multidirectional loads, and parafunctional habits such as bruxism increase stress, causing wear and surface damage that affect esthetics and comfort [27-28]. Biologically, within seconds of intraoral placement, a salivary pellicle coats the surface, and oral microbiota, including streptococci and *Candida albicans*, colonize it; these organisms produce acids such as lactic acid that lower local pH and, depending on composition, can drive more pronounced physicochemical alteration over time [29-32]. Because each patient presents a distinct combination of these factors, material selection should be individualized, with particular caution in conditions of chronic acid exposure such as gastroesophageal reflux, which produces greater surface damage and roughening of printed restorations [33-34].

Material composition and manufacturing variables: why not all printed resins age the same

Printed resins have evolved from provisional materials toward formulations intended for definitive restorations. However, incomplete polymerization, residual monomers, and subsequent monomer leaching continue to affect color stability, surface integrity, mechanical properties, and overall longevity [35]. Chemical composition is a key intrinsic determinant: materials in the same category differ in the proportions of monomers, photoinitiators, and additives, and components such as bisphenol A ethoxylated dimethacrylate (Bis-EMA), urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEGDMA), and 2-hydroxyethyl methacrylate (HEMA) can elute in varying amounts after polymerization and aqueous exposure [35]. Monomer structure and mixing ratio further modify network architecture, degree of conversion, and mechanical behavior; higher-functionality monomers can yield a more rigid network, and these traits also alter water sorption, solubility, and susceptibility to delamination [36]. Inorganic fillers modify flexibility and hardness, but behavior depends as much on filler composition and matrix interaction as on filler quantity [37].

Manufacturing parameters translate composition into final performance. Print orientation significantly affects flexural properties, with aging responses that vary by material and aqueous exposure [38]; layer thickness influences mechanical behavior [39]; and light exposure governs layer-by-layer photopolymerization and thus internal structure and surface quality [40]. The degree of conversion, which represents the proportion of reactive monomer groups converted during polymerization, is critical because insufficient conversion compromises material properties and increases residual monomer content [41].

Furthermore, the printing technology used, whether SLA, DLP, or LCD, influences precision, mechanical properties, and potentially long-term stability [42]. Post-processing is equally decisive. Post-print washing removes unpolymerized surface resin and residual monomers; however, both the washing method and duration influence its effectiveness. Ultrasonic washing can reduce residual HEMA and TEGDMA more effectively, whereas prolonged washing may reduce material flexibility. Therefore, washing protocols should be tailored to individual materials because the release of BPA, TEGDMA, UDMA, and bisphenol A glycidyl methacrylate (Bis-GMA) varies among formulations [43-44]. Post-curing time, light, and temperature jointly determine conversion, hardness, flexibility, and color, so these variables must be balanced rather than maximized [45-47]. Finally, the layered nature of printing produces interlaminar interfaces, anisotropy, internal defects, and porosity. These characteristics vary among resins intended for definitive restorations and may compromise long-term structural integrity, particularly after thermomechanical aging [48-49]. Because post-curing and aging both influence the degree of conversion, they also govern residual-monomer content and its elution: higher conversion generally lowers leaching of unreacted monomers, whereas insufficient curing or hydrolytic aging can increase it, and eluted monomers have been associated in vitro with cytotoxicity and a theoretical risk to oral soft tissues over time, although long-term in vivo consequences remain inadequately characterized [17,18,35]. Table *2* summarizes these intrinsic and processing variables.

Variable	Category	Influence on long-term behavior	Source
Monomer and photoinitiator composition	Intrinsic	Governs network structure, residual-monomer elution, color, and mechanical stability	[35,36]
Filler type and content	Intrinsic	Modifies hardness and flexibility; matrix interaction affects aging response	[37]
Print orientation and layer thickness	Processing	Alter flexural properties and anisotropy; change aging susceptibility	[38,39]
Printing technology (SLA/DLP/LCD)	Processing	Affects precision, mechanical properties, and stability	[42]
Degree of conversion	Processing	Low conversion increases residual monomer and weakens the network	[41]
Post-print washing	Post-processing	Removes residual monomer; excess time can reduce flexibility	[43,44]
Post-curing (time, light, temperature)	Post-processing	Determines conversion, hardness, flexibility, and color	[45-47]

TABLE 2: Material and manufacturing variables that determine how 3D-printed dental resins age

Composition determines a material's potential, whereas manufacturing and post-processing protocols influence how that potential is expressed.

SLA: stereolithography, DLP: digital light processing, LCD: liquid crystal display, 3D: three-dimensional

How aging changes clinical performance: mechanical, physical, and esthetic outcomes

Long-term intraoral performance depends not only on a material's intrinsic properties but also on environmental factors that influence its degradation and wear over time, ultimately affecting dimensional stability and potentially clinical success [50-52]. Mechanically, aging can progressively reduce flexural strength, fracture resistance, and fatigue resistance, potentially resulting in structural failure, deformation under occlusal loading, decreased hardness, and deterioration of functional surfaces [38,53-56]. Physically, continued exposure to the oral environment can increase water sorption and solubility, potentially affecting material composition, physical properties, and dimensional stability over time. Build angle, layer thickness, and aging conditions may further influence these changes [12,57-58]. Esthetically, the oral environment changes optical and surface characteristics, producing color change, pigmentation, and loss of gloss and translucency that compromise esthetic longevity [21,59-60].

These changes converge on clinical behavior, which differs by device type. Occlusal splints undergo fatigue and deformation from repetitive loading, and contact with saliva and temperature changes affects adaptation and function [61-63]. Removable prostheses are affected by water sorption, with dimensional change and altered tissue adaptation [12,20]. Definitive and provisional crowns are exposed to constant multidirectional masticatory forces that cause progressive wear and raise fracture risk, and aging alters marginal and internal fit [64-66]. Orthodontic appliances and directly printed aligners show deformation, wear, and progressive loss of mechanical properties, including under in vivo intraoral aging [17,67]. In

clinical settings, 3D-printed resin components such as customized brackets have shown acceptable short-term effectiveness [68], though their long-term resilience against intraoral degradation requires ongoing surveillance. Understanding each material's aging mechanism is therefore essential to appropriate case selection, and the aging pathway remains individual to both the material and the patient [33,69].

Evidence gap: accelerated aging versus real clinical aging

Laboratory studies simulate intraoral exposure using various protocols, including water storage to assess hydrolytic effects [70], thermocycling to evaluate changes in mechanical properties [65], and cyclic mechanical loading to assess fatigue resistance. In one study, a 3D-printed resin composite exhibited the lowest fatigue survival, failing well before one million cycles [71]. Combining thermocycling, artificial saliva, and mechanical fatigue better approximates intraoral conditions than isolated models, yet biological factors such as microbial adhesion are rarely integrated with thermal, mechanical, and chemical challenges [71-72]. Approaches remain fragmented, evaluating thermal, mechanical, and chemical aging separately [73], combining thermocycling with simulated mastication [69], or sequencing acidic immersion with toothbrushing [60].

Substantial heterogeneity in materials, protocols, and technologies complicates interpretation. An umbrella review of systematic reviews found considerable methodological variability and emphasized the need to standardize laboratory protocols for reliable durability assessment [50]. Some studies scale thermomechanical protocols to clinical service, describing 1.2 million cycles as roughly five years of wear [74], but cycle counts and conditions vary widely even among similar methods, complicating clinical interpretation [75-76]. Clinical evidence is accumulating, but follow-up periods remain relatively short. Additively manufactured polyetheretherketone restorations demonstrated acceptable performance at one year [77]. Resin-composite fixed dental prostheses showed acceptable performance over two years, with most failures occurring in the connector region [78]. Similarly, 3D-printed resin-matrix ceramic crowns demonstrated satisfactory two-year outcomes, although longer follow-up is still required [79]. Because compositions, post-curing, and formulations differ, results from one resin do not generalize to all printed materials [52,80-81]. Laboratory aging thus remains fundamental for material screening, but the absence of standardized multifactorial protocols and weak laboratory-to-clinical correlation limit prediction of long-term intraoral performance [76]. Table *3* compares common protocols with what they simulate.

Aging protocol	Oral factor simulated	Principal limitation	Source
Water/artificial saliva storage	Hydrolytic and salivary exposure	Omits mechanical and thermal load; salivary complexity simplified	[70]
Thermocycling	Temperature fluctuation	Isolated thermal stress; no loading or biofilm	[65,75]
Cyclic mechanical loading	Masticatory fatigue	Cycle counts vary; clinical-time equivalence uncertain	[71]
Chemical immersion and brushing	Dietary and hygiene exposure	Sequential rather than concurrent with other stressors	[60,73]
Combined multifactorial	Several factors together	Biological/biofilm component rarely integrated; not standardized	[72,74]

TABLE 3: Laboratory aging protocols and the oral factors they reproduce

Existing laboratory protocols do not fully reproduce the concurrent chemical, physical, biological, and mechanical challenges of the oral cavity, and cycle-to-time equivalence is not standardized.

Future perspectives: designing resins for the oral environment

The most credible path forward is to design materials for the oral environment rather than for the printing process or initial mechanical performance alone. Material innovation may enhance mechanical durability, fracture resistance, and resistance to degradation through nanotechnology-based reinforcement, bioinspired architectures, and crack-resistant designs, while bioactive restorative materials and smart or bio-responsive systems capable of self-healing, antibacterial activity, or responsiveness to temperature, moisture, and pH represent promising future directions [82-84]. Artificial-intelligence-assisted optimization may further improve printed materials through better parameter selection, performance prediction, defect reduction, and patient-specific manufacturing [85]. Realizing these advances will require standardized multifactorial aging protocols that incorporate a biological component and adequately powered longitudinal clinical trials so that durability, and not only initial accuracy, becomes the benchmark of clinical success.

Conclusions

The long-term success of 3D-printed dental resins should be judged not by their properties immediately after fabrication but by their capacity to maintain structural, mechanical, dimensional, esthetic, and biological stability under the combined challenges of the oral cavity. The evidence reviewed here indicates that aging is material-specific and multifactorial: intraoral materials are simultaneously exposed to moisture, salivary enzymes, thermal and pH fluctuations, dietary chemicals, microbial biofilm, and cyclic loading, and their stability is governed by material-related factors, such as composition, filler content, and network architecture, as well as manufacturing-related factors, including degree of conversion, print orientation, and post-processing conditions, and environmental aging conditions. Water sorption and plasticization, hydrolytic degradation, thermal microcracking, and mechanical fatigue can progressively erode mechanical, physical, and esthetic performance, so favorable initial properties do not ensure long-term clinical success. Laboratory aging remains essential for material screening, but methodological heterogeneity and incomplete simulation of concurrent oral environmental conditions limit its predictive value. Furthermore, available clinical evidence remains limited to relatively short follow-up periods. Progress will depend on designing resins for the oral environment rather than for the printing process alone, on standardized multifactorial aging protocols that include a biological component, and on adequately powered longitudinal clinical trials before these materials can be recommended with confidence for routine long-term use.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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