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THREE-DIMENSIONAL (3D) PRINTED COMPOSITE INLAYS AND ONLAYS: FIT ACCURACY, MECHANICAL BEHAVIOR, AND POST-PROCESSING VARIABLES: A NARRATIVE REVIEW

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ABSTRACT

Recent advances in three-dimensional (3D) printing have introduced permanent photopolymer resins as potential alternatives for indirect restorative applications. This narrative review evaluated studies published between 2018 and 2025 that investigated the internal and marginal fit, mechanical performance, and post-processing parameters of 3D-printed permanent composite inlays and onlays. Data were obtained from PubMed using keywords related to 3D printing, dental resin composites, inlay, and onlay. Both in vitro and experimental studies were included without language restriction. The majority of included studies demonstrated clinically acceptable adaptation values for 3D-printed restorations, often comparable or superior to milled equivalents. However, fracture resistance and long-term stability remained less consistent, primarily due to variability in post-curing and polymer network maturation. Within current limitations, 3D-printed permanent composites present promising potential for indirect posterior restorations, yet milling continues to represent the clinical gold standard until post-processing and material standardization are achieved.

KEYWORDS

3D Printing, Permanent Resin, Composite Inlays, Onlays, Post-Curing, Marginal Fit, Additive Manufacturing

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1. Introduction

Digital manufacturing technologies have transformed restorative dentistry, enabling more precise and individualized indirect restorations. Among these, additive manufacturing (AM) - commonly referred to as three-dimensional (3D) printing - has gained substantial attention for its ability to fabricate restorations layer by layer with high reproducibility and a high level of fit accuracy [1,2,3].

In restorative and reconstructive dentistry, 3D-printed permanent resins based on light-curable photopolymers have been developed for indirect applications such as permanent or temporary inlays, onlays and veneers. Compared to subtractive computer-aided design/computer-aided manufacturing (CAD/CAM) milling, additive workflows can minimize geometric limitations caused by bur diameter and improve reproduction of internal details. However, printed materials require careful post-curing to achieve sufficient polymer crosslinking and mechanical performance. It has been demonstrated that the most effective post-curing method is the combination of violet light and heat treatment. This approach enhances the performance and long-term durability of indirect restorations [4,5].

The aim of this review is to summarize and critically discuss the current evidence (2018-2025) concerning internal and marginal fit of 3D-printed permanent composite inlays and onlays, including the impact of post-curing and process parameters on mechanical and clinical behavior.

2. Materials and Methods

2.1 Search Strategy

This narrative review was conducted in November 2025. A structured electronic search of PubMed was performed, covering publications from January 2018 to November 2025. The following keywords were used in three searches:

1. ("3D printing"[Title/Abstract] OR "additive manufacturing"[MeSH Terms] OR "vat photopolymerization"[Title/Abstract]) AND (inlay[Title/Abstract] OR onlay[Title/Abstract]) AND (resin[Title/Abstract] OR photopolymer[Title/Abstract]) AND ("2018/01/01"[Date - Publication]: "2025/12/31"[Date - Publication])

2. (3D printed resin[Title/Abstract] OR vat photopolymerization[Title/Abstract] OR stereolithography[Title/Abstract] OR DLP printing[Title/Abstract]) and (3D printed dental resin[Title/Abstract] OR vat polymerization dental[Title/Abstract] OR SLA dental[Title/Abstract] OR DLP dental[Title/Abstract]) and (accuracy[Title/Abstract] OR marginal fit[Title/Abstract] OR internal fit[Title/Abstract]) AND (3D printed dental resin[Title/Abstract] OR vat printed dental[Title/Abstract]) AND (2018:2025[dp]) AND
3. (indirect[Title/Abstract] OR partial coverage[Title/Abstract] OR inlay[Title/Abstract] OR onlay[Title/Abstract]) AND (2018:2025[dp]) AND (inlay[Title/Abstract] OR onlay[Title/Abstract] OR indirect restoration[Title/Abstract]) AND (dental[Title/Abstract]) AND (2018:2025[dp])

No language restrictions were applied.

2.2 Eligibility Criteria

Inclusion criteria:

- studies assessing marginal and/or internal fit (µm)
- indirect dental restorations (inlay/onlay) fabricated from permanent photopolymer resins
- VAT photopolymerization (SLA or DLP)
- in vitro studies and narrative/critical reviews
- full text available
- no language restriction

Exclusion criteria:

- implant prosthodontics, orthodontics
- non-resin permanent materials as the primary target (metal, ceramic, CAD-CAM composites as primary material were excluded)
- inaccessible full text

2.3 PICO(S) Framework

Population: human teeth, extracted teeth, or laboratory printed models
Intervention: permanent photopolymer 3D printed inlay/onlay restorations
Comparison: milled restorations or comparison between different printing parameters
Outcome: marginal fit and internal fit (µm)
Study type: in vitro studies + narrative or critical reviews

2.4 Data Extraction

Data extraction was performed manually. Extracted information included: year of publication, material type, printing technology, build orientation, post-curing protocol, comparison groups, and values for marginal fit and internal fit (µm).

2.5 Outcome Measures

Primary outcomes:

- marginal fit (µm)
- internal fit (µm)

Secondary outcomes (when reported):

- fracture load / mechanical performance
- trueness / accuracy values

Exploratory outcomes:

- influence of printing parameters (orientation, layer thickness, post-curing time, resin type) on adaptation

2.6 Data Synthesis

Data were synthesized descriptively. Interpretation focused on comparative fit outcomes between 3D printing and milling, and on parameter-related differences among printed groups. No meta-analysis was performed due to methodological and measurement heterogeneity across studies.

3. Results

Across the included evidence, 3D printed indirect posterior inlays and onlays fabricated with permanent photopolymer resins demonstrated overall clinically acceptable internal and marginal fit ranges. In the majority of direct comparative studies, printed indirect restorations showed equal or superior adaptation relative to milled controls. Peskersoy et al., 2024 reported favorable mechanical and adhesion characteristics in printed indirect restorations. The technical parameters of 3D printing - such as build orientation, layer thickness, polymerization protocols during and after fabrication, resin formulation, and surface treatment procedures - are critical factors that require optimization to improve the reliability and overall success of 3D-printed restorations [6]. D'haese et al., 2025 additionally confirmed that printed composite onlays presented significantly improved marginal and internal fit when compared to milled designs, although milled restorations demonstrated higher fracture load values. The 3D-printed onlays demonstrated marginal and internal gap values of 78 µm (SD 23 µm) and 222 µm (SD 30 µm), respectively. Conversely, the milled onlays exhibited greater discrepancies, with marginal and internal gaps measuring 100 µm (SD 38 µm) and 249 µm (SD 55 µm), respectively [7]. Similar improvement in adaptation was observed by Cantó-Navés et al., 2023, moreover, the 3D-printed onlay group exhibited significantly greater consistency in gap measurements [8].

Processing parameters influenced adaptation outcomes. Özden et al., 2025 showed that post-curing time affected trueness of the printed inlays, indicating that curing protocol optimization remains directly clinically relevant [9]. Preparation design geometry also modulates adaptation behavior of printed onlays, highlighting that preparation standardization is required when translating evidence into routine clinical use [10].

Additional comparative analyses also confirmed superior or comparable adaptation of printed onlay designs using micro-CT or high-resolution silicone replica protocols. Daghrery et al., 2025 confirmed superior marginal adaptation of 3D-printed inlays in his study, whereas Pasha et al., 2023 demonstrated that their dimensional accuracy exceeded that of CAD/CAM-fabricated onlays [11, 12]. Moreover, Daher et al. (2024) demonstrated that clinically acceptable marginal adaptation can be maintained even after fatigue simulation, and three-dimensionally printed resins additionally offer advantages in terms of equipment and consumable costs [13]. In the in vitro study by Alammar et al., 2024, which evaluated resin-based fixed restorations including veneers, single crowns, and four-unit fixed dental prostheses, both the external and internal dimensional accuracy of 3D-printed restorations were found to fall within clinically acceptable limits. The mean trueness values ranged from 17 to 52 µm [22].

Supportive evidence derived from provisional analogs reinforced that printing parameters (layer thickness, exposure variables, build orientation) influence adaptation behavior. Build orientation and platform strategy impact surface quality and intaglio reproduction. The most favorable marginal and internal adaptation was achieved with provisional crowns fabricated using a 50-µm layer thickness [14]. Al-Dulaijan et al., (2024) showed that different printing orientations and post-curing times affected the internal and marginal fit of IFDPs, with both ASIGA and NextDent resins achieving clinically acceptable outcomes. However, NextDent consistently demonstrated superior overall fit, indicating a greater clinical potential [15]. 3D printing can also be applied for laminate veneers. CBCT-based evaluation of marginal and internal fit in veneers fabricated using 3D printing and CAD/CAM milling showed that the 3D-printed veneers exhibited lower marginal and internal discrepancies than the milled ones, indicating superior clinical adaptation. Therefore, additive manufacturing proved to be more precise than traditional subtractive fabrication methods [16]. Post-curing and polymer network development may further modulate mechanical integrity [5, 17], suggesting that polymer curing strategy remains one of the most consequential determinants of final dimensional accuracy of printed permanent resins.

Overall, current evidence indicates that 3D printed indirect posterior onlays fabricated with permanent composite resins can achieve clinically acceptable internal and marginal fit, with multiple studies showing fit superiority over milled restorations, although fracture resistance performance still requires optimization.

Multiple printed inlay/onlay studies demonstrate that dimensional accuracy is not only material-dependent, but strongly workflow-dependent. Post-curing energy dose and thermal assist modulate polymer network conversion and therefore trueness [4, 5, 9, 17]. Preparation design also influences adaptation, particularly axial wall divergence and internal rounding [10]. Improvement in internal fit over milled controls in several studies suggests that optimization of parameters may allow printed indirect restorations to reach "precision-driven" workflows, reducing cumulative subtractive error sources [7, 8, 12]. Moreover, in a comparative study of subtractive and additive fabrication methods, no significant differences in marginal gap width were identified. The mean marginal discrepancies ranged from 59 to 84 µm. Both techniques were deemed suitable for producing indirect restorations such as onlays [23].

4. Discussion

Across the present literature, 3D printed composite inlays and onlays demonstrated clinically acceptable marginal and internal fit, with multiple studies reporting equal or superior adaptation compared with milled indirect restorations [6, 7, 8, 11, 12]. However, fracture resistance remains consistently higher in milled restorations, indicating that adaptation superiority does not necessarily translate into higher structural durability [7, 21]. In summary, improved fit in printed restorations is likely associated with reduced cumulative subtractive error sources and voxel-based additive trueness; nevertheless, inferior mechanical response appears strongly linked to polymer network maturity and post-polymerization variability [4, 5, 9, 17]. Supporting evidence from provisional analog literature and veneer partial coverage studies further reinforces that build orientation, preparation geometry, curing energy, temperature assist, and surface treatment parameters modulate final dimensional accuracy [14, 15, 16]. A synthesis of resin research confirms that future advancements will depend more on the optimization of post-processing protocols and strategies for stabilizing resin chemistry than on additional comparative studies alone, and that optimal shear bond strength in high-filler 3D printing materials can be achieved through the combined application of silane and an appropriate bonding agent [1, 3, 18, 19, 20]. In summary, 3D printed indirect composite restorations remain highly promising, but based on current mechanical reliability evidence, milled indirect restorations should still be considered the clinical gold standard at the present time, before fully standardized curing frameworks and high-consistency resin polymer systems are established.

5. Limitations

Most included studies were in vitro, limiting direct clinical extrapolation of performance outcomes. Fit evaluation protocols were not standardized across studies, with silicone replica, micro-CT, and digital internal gap quantification used heterogeneously, creating methodological variability in measurement comparability [2]. Mechanical outcomes were additionally influenced by different resin chemistries, printing platforms, and curing strategies, making direct mechanical benchmarking challenging [6, 7, 12, 18]. There was limited long-term fatigue and aging simulation for posterior occlusal loading conditions, and the clinical literature remains insufficient to define long-term survival equivalence with milled restorations. Therefore, interpretation of mechanical superiority or equivalence should remain cautious until consistent long-term evidence becomes available.

6. Conclusions

Current evidence demonstrates that 3D-printed composite inlays and onlays fabricated with high-performance photopolymer resins can achieve clinically acceptable internal and marginal fit, frequently comparable or superior to milled restorations. However, mechanical performance and long-term predictability remain less consistent, primarily due to variability in post-processing protocols and resin polymer maturation. Within the limits of in vitro data, 3D printing represents a promising complement - not yet a replacement - to conventional milling for indirect posterior restorations. Continued research focused on standardized curing parameters, resin chemistry stabilization, and fatigue-aging validation will be essential before 3D-printed permanent composites can be considered a fully equivalent alternative in clinical dentistry.

Disclosure
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Software: Łukasz Krzystek, Michał Mazurek
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