



Adaptation, Trueness and Precision of Inlay and Onlay Restorations Fabricated By Additive and Subtractive Manufacturing: A Systematic Review

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Abstract Objectives: The accuracy of indirect restorations plays a critical role in their longevity and clinical performance. Inlays and onlays as conservative alternatives to full crowns, require optimal marginal and internal adaptation to prevent microleakage, recurrent caries and loss of bond integrity. With the increasing integration of Three-Dimensional (3D) printing in dentistry, a systematic evaluation of additive versus subtractive fabrication for these restorations is warranted. **Objective:** This systematic review aimed to synthesize evidence comparing the adaptation, trueness and precision of inlay and onlay restorations fabricated by Additive Manufacturing (AM) with those produced by Subtractive Milling (SM) or conventional methods. **Methods:** This review followed the PRISMA 2020 guidelines. A comprehensive search was conducted in PubMed, Embase, Web of Science and Scopus from inception to October 30, 2025. Eligible studies included in vitro experiments on natural teeth or standardized dies prepared for inlay or onlay restorations, with AM as intervention and SM or conventional fabrication as comparators. Outcomes of interest were Marginal Gap (MG), Internal Gap (IG), Absolute Marginal Discrepancy (AMD), Overall Discrepancy (OD), trueness and precision. Risk of bias was assessed with the QUIN tool. **Results:** A total of 866 records were identified through database searches. After removal of duplicates and screening against eligibility criteria, seven in vitro studies involving 402 specimens were included in the review. Across studies, AM restorations demonstrated MG values between 54-290 μm , generally comparable to SM (58-509 μm) and conventional methods (50-108 μm). IG values for AM ranged from 35-280 μm versus 62-509 μm for SM. Trueness outcomes often favored SM, particularly with zirconia, while limited evidence suggested favorable precision or reproducibility with AM, although the metrics used differed across studies. Many reported gap measurements were within the historically cited 120- μm benchmark, although substantial method- and site-specific exceedances were observed. Risk of bias was graded as low in 2 studies and medium in 5 studies. **Conclusion:** Under laboratory conditions, additive manufacturing yielded adaptation comparable to subtractive milling and conventional methods, although outcomes varied among studies and measurement approaches. Trueness often favored certain milled materials, while the limited evidence on precision and reproducibility sometimes favored AM. These findings support AM as a potentially viable restorative approach. However, clinical equivalence or superiority cannot be established from the currently available in vitro evidence.

Key Words 3D Printing, CAD/CAM, Partial Coverage Restorations, Marginal Fit, Internal Fit, Digital Dentistry

INTRODUCTION

Indirect partial-coverage restorations such as inlays and onlays remain an important treatment modality when extensive tooth structure loss cannot be predictably managed with direct restorations [1]. Compared with full crowns, these restorations are more conservative, maintain cuspal integrity and distribute functional stresses in a favorable

way, thereby preserving long-term tooth vitality and strength [2]. Their clinical longevity is strongly influenced by the quality of marginal and internal adaptation. Inadequate fit has been associated with increased microleakage, recurrent caries, compromised bond durability and periodontal inflammation [3,4]. The concept of a clinically acceptable marginal gap has long been discussed, with McLean and von Fraunhofer's *in vivo*

estimate of approximately 120 μm often cited as a threshold [5]. However, this value represents a historically cited benchmark rather than a universally applicable clinical cutoff, as acceptable adaptation may vary according to restoration type, material, measurement technique and clinical conditions. Fabrication methods have evolved considerably over the past three decades. Conventional lost-wax techniques while reliable, are highly operator dependent and subject to inaccuracies from impression, casting and laboratory steps [6]. The introduction of Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) facilitated a transition to subtractive milling of ceramics and hybrid materials. This method improves standardization, reduces laboratory steps and enhances reproducibility. Yet, it is limited by material waste, bur diameter restrictions and potential loss of detail in internal contours [7,8].

Additive Manufacturing (AM), often referred to as Three-Dimensional (3D) printing, has been introduced more recently into restorative dentistry. Unlike milling, AM fabricates restorations layer-by-layer, allowing reproduction of complex geometries, minimal material waste and the possibility of chairside or near-chairside workflows [9,10]. Technologies such as Stereolithography (SLA), Digital Light Processing (DLP) and Liquid Crystal Display (LCD) printing have been widely explored for dental applications [11-13]. Beyond provisional restorations, there is growing interest in permanent resin-based composites and hybrid ceramics produced by AM, with early studies demonstrating promising mechanical and esthetic properties [14-16]. Accuracy outcomes are usually reported in three main categories. Trueness refers to the closeness of the fabricated object to its digital design [17]. Precision describes the reproducibility of repeated fabrications [17]. Adaptation outcomes are assessed by measuring marginal and internal gaps [18]. In this review, “fit” refers broadly to restoration-tooth adaptation assessed through gap measurements, whereas “accuracy” is used as an overarching concept encompassing trueness and precision. Accordingly, adaptation, trueness and precision are considered related but distinct outcomes. Several investigations on crowns and veneers have shown that milled restorations often display higher trueness, whereas printed restorations achieve superior precision and, in some cases, smaller internal gaps [19-20]. Systematic reviews have reported broadly comparable adaptation between additive and subtractive methods, though variations depend on material type, printer technology and evaluation methodology [21-22].

Inlays and onlays, however, present specific challenges not fully addressed in previous reviews. Their internal design includes defined line angles and partial cuspal coverage, which demand accurate reproduction to achieve proper seating and load distribution [23]. Furthermore, inlay and onlay restorations are frequently indicated in posterior teeth under high occlusal loads, where marginal integrity is critical for clinical success [24]. Despite the increasing availability of printable restorative resins and hybrid materials, evidence focused exclusively on inlays and onlays remains limited. A

systematic assessment of this subset is therefore necessary to clarify whether additive manufacturing can match or surpass subtractive and conventional techniques in terms of adaptation, trueness and precision. This systematic review aims to synthesize available *in vitro* evidence on the marginal and internal fit, trueness and precision of inlay and onlay restorations fabricated by additive manufacturing compared with subtractive milling and conventional methods.

METHODS

Protocol and Registration

This systematic review was carried out according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) recommendations [25] and was prospectively registered in the Open Science Framework database on Sep 26, 2025 (osf.io/wpqme/overview).

Research Question

The review addressed the following focused question: Among inlay and onlay restorations, how do additive (3D-printed) techniques compare with subtractive (milled) and conventional fabrication methods regarding marginal and internal fit, trueness and precision? Subtractive milling was considered the principal comparator, while conventional fabrication methods were considered an additional comparator when reported by eligible studies.

Eligibility Criteria

Studies were considered eligible if they met the following inclusion criteria:

- **Population:** Natural teeth or standardized dies prepared for inlay and onlay restorations
- **Intervention:** Additive Manufacturing (3D printing)
- **Comparator:** Subtractive manufacturing (milling) and/or conventional fabrication
- **Outcomes:** Marginal Gap (MG), Internal Gap (IG), Absolute Marginal Discrepancy (AMD), Overall Discrepancy (OD), Trueness (RMS), Precision (TOR).
- **Study Design:** *In vitro* experimental studies
- **Language:** English
- **Time Frame:** Up to October 2025

Exclusion Criteria Included:

- Studies on crowns, veneers, or without separate inlay or onlay data
- Clinical case reports, reviews, or expert opinions
- Studies lacking evaluation of adaptation or trueness

Information Sources

A comprehensive electronic search was conducted in PubMed/MEDLINE, Embase, Web of Science and Scopus from inception to October 30, 2025. The strategy combined MeSH terms and free-text keywords related to inlays, onlays, occlusal veneers/table-tops, additive manufacturing (3D printing), subtractive manufacturing (milling/CAD-

CAM) and adaptation outcomes (marginal/internal gap, absolute marginal discrepancy, trueness, precision, accuracy). Search strings were adapted for each database (Table 1). In addition, the reference lists of all included studies and relevant reviews were screened manually to identify further eligible publications. Broader partial-coverage terms, including occlusal veneers, table-tops and occlusal overlays, were incorporated into the search to maximize sensitivity; however, studies were eligible for inclusion only when inlay or onlay data were reported separately. Database searches were restricted to English-language records in accordance with the predefined eligibility criteria. All four electronic database searches were last conducted on October 30, 2025.

Study Selection

Two reviewers independently screened titles and abstracts. Full texts of potentially relevant articles were retrieved and assessed against the eligibility criteria. Disagreements were resolved by discussion until consensus was achieved. A third reviewer was available for unresolved disagreements.

Data Extraction

Data were independently extracted by two reviewers using a standardized data-extraction form. Disagreements were resolved by consensus. From each included study, the following data were extracted: Main author and year, restoration type, sample size, fabrication method, fabrication materials, measurement method (replica, micro-CT, CBCT, digital superimposition), evaluation sites (marginal gap, internal gap, absolute marginal discrepancy, trueness/precision) and main results.

Risk of Bias Assessment

The methodological quality of the included *in vitro* studies was assessed using the Quality Assessment Tool for In Vitro

Studies (QUIN) [26], which was specifically developed and validated for methodological assessment of *in vitro* dental studies. This tool comprises twelve domains: clarity of aims, sample size calculation, sampling technique, use of comparison groups, methodological details and standardization, operator details, randomization, outcome measurement, assessor details, blinding, statistical analysis and presentation of results. Each domain is scored 0 (not reported), 1 (inadequately reported), or 2 (adequately reported). The overall score for each study is calculated as a percentage of the maximum possible score and then graded as low risk of bias (>70%), medium risk (50-70%), or high risk (<50%). Two reviewers performed the assessment independently; disagreements were resolved by discussion until consensus was reached.

Data Synthesis

A qualitative synthesis was undertaken because substantial heterogeneity in restoration type, restorative materials, fabrication technologies, measurement methods, evaluation sites and outcome definitions precluded meaningful quantitative pooling.

RESULTS

Study Selection

The electronic search yielded 866 records. After the removal of 114 duplicates, 752 titles and abstracts were screened. Of these, 742 records were excluded for not meeting the eligibility criteria. The full text of 10 articles was then assessed and three studies were excluded (two focused on restorations other than inlays or onlays and one due to ineligible study design, Supplementary file 1). Finally, seven *in vitro* studies involving 402 specimens fulfilled the eligibility criteria and were included in the qualitative synthesis (Figure 1).

Table 1: Detailed Search Strategies Applied Across Electronic Databases

Electronic Database	Search Strategy
MEDLINE	("Three-Dimensional Printing"[Mesh] OR "stereolithography"[Mesh] OR "3D printing"[Title/Abstract] OR "Three-Dimensional Printing"[Title/Abstract] OR "additive manufacturing"[Title/Abstract] OR stereolithograph*[Title/Abstract] OR "digital light processing"[Title/Abstract] OR DLP[Title/Abstract] OR SLA[Title/Abstract] OR LCD[Title/Abstract]) AND (inlay*[Title/Abstract] OR onlay*[Title/Abstract] OR "occlusal veneer*[Title/Abstract] OR tabletop*[Title/Abstract] OR "table-top*[Title/Abstract] OR "occlusal overlay*[Title/Abstract] OR "partial coverage"[Title/Abstract]) AND ("marginal gap"[Title/Abstract] OR "internal gap"[Title/Abstract] OR "absolute marginal discrepancy"[Title/Abstract] OR AMD[Title/Abstract] OR "overall discrepancy"[Title/Abstract] OR trueness[Title/Abstract] OR precision[Title/Abstract] OR accuracy[Title/Abstract] OR "prosthesis fit"[Mesh]) AND (CAD/CAM[Title/Abstract] OR mill*[Title/Abstract] OR "subtractive manufactur*[Title/Abstract] OR conventional[Title/Abstract]) NOT (implant*[Title/Abstract] OR abutment*[Title/Abstract] OR crown*[Title/Abstract] OR bridge*[Title/Abstract])
Embase	('three dimensional printing'/exp OR 'stereolithography'/exp OR 'additive manufacturing'/exp OR '3d printing':ab,ti OR stereolithograph*:ab,ti OR 'digital light processing':ab,ti OR dlp:ab,ti OR sla:ab,ti OR lcd:ab,ti) AND (inlay*:ab,ti OR onlay*:ab,ti OR 'occlusal veneer*:ab,ti OR tabletop*:ab,ti OR 'table-top*:ab,ti OR 'occlusal overlay*:ab,ti OR 'partial coverage':ab,ti) AND ('marginal gap':ab,ti OR 'internal gap':ab,ti OR 'absolute marginal discrepancy':ab,ti OR amd:ab,ti OR 'overall discrepancy':ab,ti OR trueness:ab,ti OR precision:ab,ti OR accuracy:ab,ti OR 'prosthesis fit'/exp) AND (cad:ab,ti OR 'cad/cam':ab,ti OR mill*:ab,ti OR 'subtractive manufactur*:ab,ti OR conventional:ab,ti) NOT (implant*:ab,ti OR abutment*:ab,ti OR crown*:ab,ti OR bridge*:ab,ti)
Web of Science	TS=(("3D printing" OR "Three-Dimensional Printing" OR "3D-print*" OR "additive manufacturing" OR stereolithograph* OR "digital light processing" OR DLP OR SLA OR LCD) AND (inlay* OR onlay* OR "occlusal veneer*" OR tabletop* OR "table-top*" OR "occlusal overlay*" OR "partial coverage") AND ("marginal gap" OR "internal gap" OR "absolute marginal discrepancy" OR "overall discrepancy" OR trueness OR precision OR accuracy OR "prosthesis fit" OR fit) AND ("CAD/CAM" OR mill* OR "subtractive manufactur*" OR conventional))
Scopus	TITLE-ABS-KEY (("3D printing" OR "Three Dimensional Printing" OR "Three-Dimensional Printing" OR "additive manufacturing" OR stereolithograph* OR "digital light processing" OR DLP OR SLA OR LCD) AND (inlay* OR onlay* OR "occlusal veneer*" OR tabletop* OR "table-top*" OR "occlusal overlay*" OR "partial coverage") AND ("marginal gap" OR "internal gap" OR "absolute marginal discrepancy" OR AMD OR "overall discrepancy" OR trueness OR precision OR accuracy OR "prosthesis fit") AND (CAD/WAM OR CAD/CAM OR mill* OR "subtractive manufactur*" OR conventional)) AND NOT (implant* OR abutment* OR crown* OR bridge*)

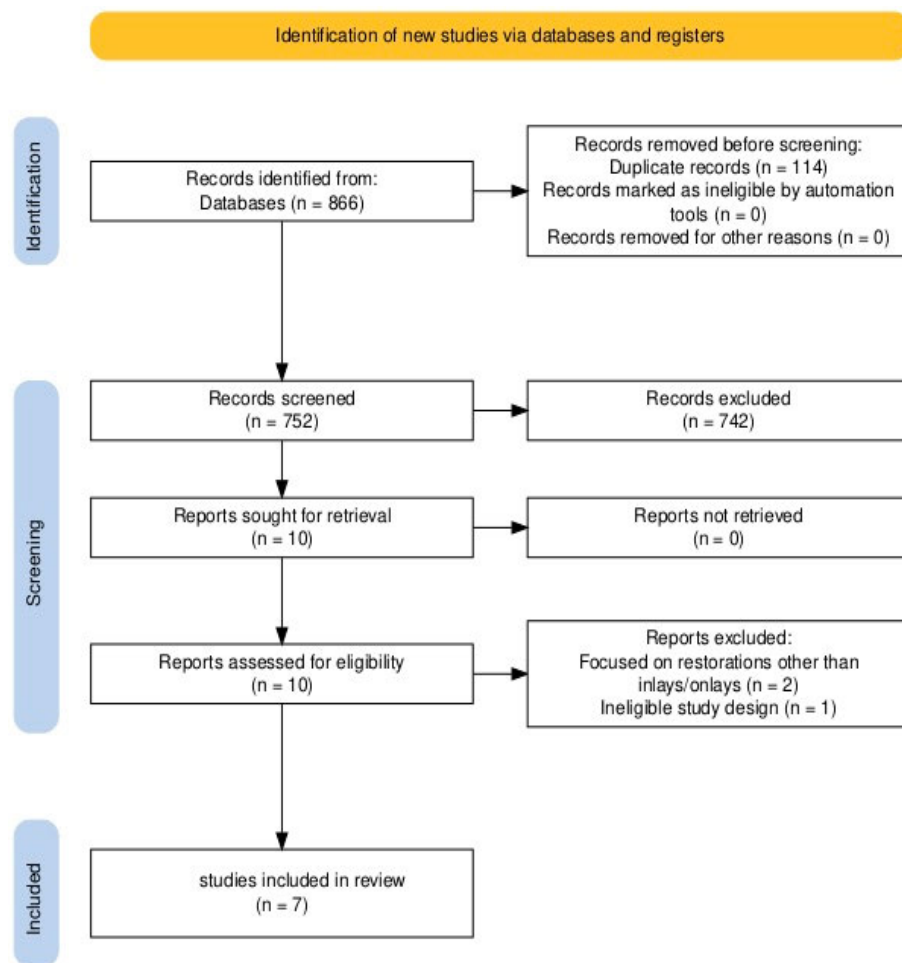


Figure 1: PRISMA2020 Flow Diagram of the Study Selection Process

Study Characteristics

The seven included studies were published between 2019 and 2025 and all were *in vitro* experimental investigations [27-33]. Sample sizes ranged from 6 to 180 specimens, with restorations fabricated as either inlays or onlays. All studies compared additive manufacturing (3D printing) with either subtractive CAD/CAM milling or conventional indirect fabrication techniques. A variety of restorative materials were tested, including resin-based composites, hybrid ceramics and zirconia. Additive approaches relied mainly on Digital Light Processing (DLP), Stereolithography (SLA), or LCD-based printing, whereas subtractive methods employed CAD/CAM milling of resin nanoceramics, hybrid ceramics, or zirconia. Conventional groups, where included, involved indirect composite resins. Evaluation methods varied across studies: micro-CT was applied in three studies [27,29,31], replica with microscopic analysis in three [27-29], digital superimposition in three [28,30,32] and CBCT in one [33]. Reported outcomes focused primarily on Marginal Gap (MG) and Internal Gap (IG). Additional outcomes included Absolute Marginal Discrepancy (AMD) and Overall Discrepancy (OD) [33], as well as digital accuracy metrics such as Trueness (RMS) and Precision

(TOR) [28,32]. A detailed overview of study design, materials, measurement approaches and results is presented in Table 2.

Risk of Bias within Studies

Methodological quality was assessed using the QUIN tool (Table 3). Two studies were judged low risk of bias [32,33], while the remaining five were medium risk [27-31]. Most reports stated objectives clearly, described procedures in adequate detail, applied appropriate statistics and presented complete results. The main shortcomings were the absence of *a priori* sample-size calculations in all but two studies [32,33], which both reported formal power analyses. Additionally, assessor repeatability was explicitly documented only in Özden and Uygün [32]. Randomization procedures were generally under-reported and none of the studies described blinding during specimen preparation, measurement, or analysis (Supplementary file 2).

Results of Individual Studies and main Findings

Marginal Gap: All seven studies assessed marginal adaptation. Reported mean MG values for 3D-printed restorations ranged from 54 μm [28] to 290 μm [33], while milled restorations ranged from 61 μm [31] to 509 μm [27].

Table 2: Overview of the Included Studies

Study and year	Sample size	Restoration type	Fabrication methods	Fabrication materials	Measurement method	Outcomes evaluated	Main results
Ahlholm <i>et al.</i> [27]	n=6 teeth; paired restorations (milled vs printed)	Inlays/onlays	SM: CAD/CAM milling (CEREC MC XL) AM: MultiJet printing (ProJet 3500 HDMax)	SM: Lava Ultimate (3M) AM: VisiJet M3 Crystal	Micro-CT (7 MD points) Replica/weight	MG, IG; internal fit	MG/IG (micro-CT): AM 68 ± 23 to 182 ± 222 vs SM 166 ± 67 to 509 ± 126 ; AM < SM at 5/7 sites ($p < 0.05$). Replica: AM ~40-60% smaller internal gap than SM.
Lim <i>et al.</i> [28]	n=52 inlays; 4 groups (n=13)	Class II inlays	Conv.; SM; AM (DLP)	Conv.: Tescera (TS) SM: Lava Ultimate (LU), Zolid Fx (ZR) AM: NextDent C&B	Replica (6 pts) 3D accuracy (RMS)	MG, IG; trueness; precision	MG: TS 108 ± 67 , LU 119 ± 46 , ZR 58 ± 15 , AM 54 ± 16 (ZR, AM < TS, LU; $p < 0.05$). IG: TS 103 ± 44 , AM 82 ± 8 , ZR 96 ± 13 , LU 169 ± 43 (worst; >120). Trueness (RMS): ZR 33 ± 7 best; AM 41 ± 5 ; TS 47 ± 15 ; LU 49 ± 17 (ZR < LU; $p < 0.05$). Precision (RMS): AM 20 ± 2 , ZR 25 ± 2 < TS 46 ± 6 < LU 65 ± 13 ($p < 0.001$).
Pasha <i>et al.</i> [29]	n=20 teeth; 2 groups (n=10 SM; n=10 AM)	Mandibular molar onlays	SM: CAD-CAM milling AM: 3D printing	SM: Aidite zirconia AM: Shining 3D Bio Clear SG01	Replica + stereomicroscope Micro-CT	MG, IG (site-specific)	Replica: Occlusal AM 502 ± 85 vs SM 982 ± 126 ($p < 0.001$); Prox 445 ± 83 vs 789 ± 134 ($p < 0.001$); Axial 214 ± 60 vs 359 ± 132 ($p = 0.005$). Micro-CT: Occlusal AM 93 ± 5 vs SM 127 ± 21 ($p < 0.001$); Prox 78 ± 8 vs 87 ± 10 ($p = 0.03$); Axial 35 ± 8 vs 62 ± 10 ($p < 0.001$) → AM < SM at all sites.
Cantó-Navés <i>et al.</i> [30]	n=44 onlays; 2 groups (n=22 SM; n=22 AM)	Onlays (resin molar)	SM: 5-axis milling AM: SLA printing	SM: Graphene-PMMA (Acrylgraph) AM: BEGO Permanent Crown resin	Digital superimposition (triple-scan)	Marginal, internal, central gaps; reproducibility	Marginal: AM 138 ± 41 vs SM 217 ± 107 ($p < 0.05$). Internal: AM 102 ± 59 vs SM 161 ± 68 ($p < 0.05$). Central: AM 115 ± 7 vs SM 226 ± 11 ($p < 0.05$). Reproducibility: lower SDs for AM at margins.
Peskersoy and Oguzhan [31]	n=60 teeth; 3 arms (n=20 AM; n=20 SM; n=20 Conv.)	Class II onlays	AM (DLP); SM (milling); Conv.	AM: VarseoSmile Crown Plus SM: Cerasmart Conv.: Signum	Micro-CT (regional MG) Bond testing	MG; voids/porosity; bond strength	MG (overall): AM 81, SM 61, Conv 97; all <120. SM < Conv ($p = 0.007$); AM vs SM ns. Regional MG: occlusal highest in AM; middle highest in Conv; cervical ns. Bond (MPa): SM $34.8 \rightarrow 26.9$ ($p = 0.036$); AM $12.5 \rightarrow 11.4$ (ns); Conv $16.2 \rightarrow 17.3$ (ns) → SM > AM < Conv. Porosity: SM lowest.
Özden and Uygun, [32]	n=180 inlays; 3 resins × 3 post-cures × n=20	Inlays	AM (LCD/MSLA)	Senertek P-Crown V3; BEGO Crown Plus; Saremco Crowntec	Digital superimposition (RMS, TOR)	Trueness (RMS), precision (TOR)	Trueness (RMS, μ m): Crowntec 80 ± 18 (best), BEGO 101 ± 17 , Senertek 114 ± 17 ($p < 0.001$). TOR (%): Crowntec 94.6, BEGO 90.6, Senertek 80.2 ($p < 0.001$). Post-cure effect: RMS $103 \rightarrow 95$ (2k→6k; $p = 0.046$); TOR $89.8\% (4k) > 87.5\% (6k)$; ($p = 0.005$).
Daghrery <i>et al.</i> [33]	n=40 dies; 4 groups (n=10 each)	Class II MOD inlays	AM (DLP) ×2; SM; Conv.	AM: Crownplus (PVC), TriniQ (PVT) SM: VITA Enamic Conv.: Gradia Plus	CBCT (MD/BL sections)	MG, IG, AMD, OD	AMD: PVC 420 ± 50 , PVT 290 ± 50 , MVE 480 ± 60 , CGP 250 ± 130 . MG: PVC 290 ± 60 , PVT 210 ± 50 , MVE 330 ± 60 , CGP 50 ± 70 . IG: PVC 280 ± 50 , PVT 270 ± 70 , MVE 310 ± 50 , CGP 140 ± 60 . OD: PVC 310 ± 50 , PVT 260 ± 50 , MVE 340 ± 40 , CGP 150 ± 40 (all $p < 0.05$). AM (PVT) < AM (PVC); SM (MVE) worst; Conv (CGP) best.

AM, Additive Manufacturing; SM, Subtractive Manufacturing; Conv./CT, Conventional Technique; MG, Marginal Gap; IG, Internal Gap; AMD, Absolute Marginal Discrepancy; OD, Overall Discrepancy; RMS, Root Mean Square deviation; TOR, Total Overlap Ratio; 3D, Three-Dimensional Printing group; MD, Mesiodistal section; BL, Buccolingual section; μ m, micrometer; MPa, megapascal; TC, thermocycling; ns, not significant; TS, Tescera resin; LU, Lava Ultimate; ZR, Zolid Fx zirconia; PVC, VarseoSmile Crownplus resin; PVT, VarseoSmile TriniQ resin; MVE, VITA Enamic; CGP, Gradia Plus; Micro-CT, Micro-Computed Tomography; CBCT, Cone Beam Computed Tomography

Table 3: Risk of Bias Assessment of the Included Studies using the QUIN Tool

Study and year	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	Total	Final %	Grade
Ahlholm <i>et al.</i> [27]	2	0	1	2	2	1	0	2	0	0	2	2	14	63.6	Medium risk
Lim <i>et al.</i> [28]	2	0	1	2	2	0	0	2	0	0	2	2	13	54.2	Medium risk
Pasha <i>et al.</i> [29]	2	0	1	2	2	0	0	2	0	0	2	2	13	54.2	Medium risk
Cantó-Navés <i>et al.</i> [30]	2	0	1	2	2	0	0	2	0	0	2	2	13	54.2	Medium risk
Peskersoy and Oguzhan [31]	2	0	1	2	2	1	1	2	0	0	2	2	15	62.5	Medium risk
Özden and Uygun [32]	2	2	1	2	2	2	1	2	2	0	2	2	18	75.0	Low risk
Daghrery <i>et al.</i> [33]	2	2	2	2	2	1	1	2	1	0	2	2	19	79.2	Low risk

D1, clarity of aims/objectives; D2, sample size calculation/justification; D3, sampling technique; D4, comparison/control group; D5, methodological details and standardization; D6, operator details/calibration; D7, randomization; D8, outcome measurement method (validity/reliability); D9, outcome assessor details/calibration; D10, blinding; D11, statistical analysis; D12, presentation of results

Conventional techniques produced MG values between 50 μ m [33] and 97 μ m [31]. In several studies, AM demonstrated smaller or comparable marginal gaps relative to SM, although results varied according to the material, site and measurement method. While many measurements were within the historically cited 120- μ m benchmark, important exceedances were observed, particularly in Daghrery *et al.* [33] and in the replica-based measurements of Pasha *et al.* [29].

Internal Gap

Five studies reported internal adaptation. For AM, IG values ranged from 35 μ m [29] to 280 μ m [33]. For SM, the range was 62 μ m [29] to 509 μ m [27]. Conventional techniques showed IG values of 140 μ m [33] to 169 μ m [28]. Across studies, AM often demonstrated smaller internal gaps than SM in specific comparisons; however, considerable variability was evident among materials and measurement

approaches and some AM measurements substantially exceeded the historically cited 120- μ m benchmark.

Absolute Marginal Discrepancy and Overall Discrepancy

Only Daghrery *et al.* [33] investigated AMD and OD using CBCT. AM restorations showed AMD values between 290-420 μ m, whereas SM (VITA Enamic) reached 480 μ m and conventional Gradia Plus achieved the smallest value (250 μ m). Similarly, OD ranged from 260 μ m (AM TriniQ) to 340 μ m (SM Enamic), with the conventional group again performing best. Because AMD and OD were evaluated in only one included study, these findings should be considered study-specific.

Trueness and Precision

Two studies assessed trueness using RMS-based digital analysis [28,32]. Reported RMS trueness values for AM ranged from 41 μ m [28] to 114 μ m [32], while the comparative groups in Lim *et al.* [28] ranged from 33 to 49 μ m. Precision was reported using different metrics and was therefore interpreted separately. Lim *et al.* [28] assessed precision using RMS deviation and reported lower values for AM (20 $\pm$ 2 μ m) than the compared groups (25-65 μ m), indicating greater repeatability in that study. Özden and Uygun [32] assessed precision among AM materials using Total Overlap Ratio (TOR), which ranged from approximately 80% to 95%. Cantó-Navés *et al.* [30] additionally reported reproducibility based on the variability of gap measurements. Because RMS, TOR and variability-based reproducibility represent different measures, they were not directly compared across studies (Table 4).

DISCUSSION

The synthesis of the included studies suggests that AM can achieve adaptation comparable to SM for inlay and onlay restorations under selected laboratory conditions. Although many reported marginal and internal gap measurements were within the historically cited 120- μ m benchmark proposed by McLean and von Fraunhofer [5], substantial exceedances were also observed and this benchmark should not be regarded as a universal indicator of clinical acceptability. Considering the heterogeneity in study designs, materials and measurement approaches, the available evidence indicates a trend toward comparable (and in some individual comparisons smaller) gap measurements with AM rather

than definitive superiority over SM. Trueness favored milling in some comparisons, particularly when zirconia was used. Evidence from restoration types outside the eligibility criteria is considered here only as contextual evidence and was not included in the present systematic synthesis. These findings are consistent with a growing body of literature beyond the present review. In a recent comparison of zirconia occlusal veneers, printed restorations exhibited significantly smaller internal discrepancies and absolute marginal discrepancies than CAD/CAM-milled specimens, with all values within clinically acceptable limits [34]. A recent synthesis of laminate veneers and intracoronary restorations likewise reported superior or comparable trueness and fit for AM relative to SM, noting that outcomes are influenced by material type and preparation design [35]. At the same time, broader, cross-indication meta-analyses caution that trueness may favor milling, whereas precision tends to be higher with AM and intaglio fit is often comparable between the two methods-patterns that mirror our findings for inlays/onlays [36,37].

Nevertheless, the relative performance of AM and SM should also be interpreted in the context of material composition, printer technology, milling system, resin formulation, printing orientation, post-curing conditions and restoration-design parameters, each of which may independently influence dimensional accuracy and adaptation. Recent systematic reviews and meta-analyses on tooth-supported crowns and fixed prostheses report a consistent pattern: milling tends to achieve lower trueness error, whereas 3D printing often shows higher precision/repeatability, with intaglio fit generally comparable between methods [36,37]. This pattern is echoed in individual comparative studies of monolithic zirconia crowns, where milled restorations frequently exhibit superior trueness while printed groups maintain high precision within clinically acceptable bands [38,39]. These external findings align with our synthesis, in which several included studies indicated better reproducibility for AM, whereas zirconia milling produced the lowest trueness deviations in specific comparisons [28]. Overall, the available evidence suggests that both AM and SM can achieve acceptable adaptation under selected laboratory conditions, although performance varies according to the material, workflow, measurement method and evaluated site.

Table 4: Summary of Reported Outcomes for Inlay and Onlay Restorations Fabricated by Additive Manufacturing (AM), Subtractive Manufacturing (SM) and Conventional Techniques

Outcome	AM (3D printing)	SM (milling)	Conventional	Studies contributing
Marginal gap (MG, μ m)	54-290	58-509	50-108	Ahlholm <i>et al.</i> [27]; Lim <i>et al.</i> [28]; Pasha <i>et al.</i> [29]; Cantó-Navés <i>et al.</i> [30]; Peskersoy and Oguzhan [31]; Daghrery <i>et al.</i> [33]
Internal gap (IG, μ m)	35-280	62-509	103-140	Ahlholm <i>et al.</i> [27]; Lim <i>et al.</i> [28]; Pasha <i>et al.</i> [29]; Daghrery <i>et al.</i> [33]
AMD (μ m)	290-420	480	250	Daghrery <i>et al.</i> [33]
OD (μ m)	260-310	340	150	Daghrery <i>et al.</i> [33]
Trueness (RMS, μ m)	41-114	33-49	$\approx$ 47	Lim <i>et al.</i> [28]; Özden and Uygun [32]
Precision (RMS, μ m)	20 $\pm$ 2	25-65	46 $\pm$ 6	Lim <i>et al.</i> [28]
Precision (TOR, %)	80.2-94.6	—	—	Özden and Uygun [32]

AM, Additive Manufacturing (3D printing); SM, Subtractive Manufacturing (CAD/CAM milling); MG, Marginal Gap; IG, Internal Gap; AMD, Absolute Marginal Discrepancy; OD, Overall Discrepancy; RMS, Root Mean Square deviation (trueness measure); TOR, Total Overlap Ratio (precision measure); μ m, micrometer

Some comparisons favored AM for marginal or internal adaptation, whereas milling showed advantages in trueness in specific material systems. Evidence regarding precision and reproducibility remains limited and metric-dependent. Accordingly, the current findings support AM as a promising alternative to milling for partial-coverage indirect restorations but do not establish clinical equivalence or superiority. Importantly, laboratory gap values below a specific benchmark should not be interpreted as proof of clinical success, which is also influenced by cement thickness, bonding, material properties, biological conditions, occlusal loading and aging.

Limitations

This review was conducted in accordance with PRISMA guidelines, with comprehensive database searching, predefined eligibility criteria and standardized data extraction procedures (Supplementary file 3). However, the available body of evidence is limited to laboratory experiments, most with relatively small sample sizes and short-term testing conditions. Only two studies [32,33] reported a priori sample-size calculation and only one [33] addressed assessor calibration. Blinding was absent across all studies and randomization procedures were either insufficiently described or not applied. In addition, clinical variables such as saliva, masticatory forces, or long-term aging protocols were either simulated partially or not considered, which restricts the direct translation of these results to clinical practice. Although a comprehensive and systematic search was undertaken across four major databases and supplemented by manual screening, some limitations must be acknowledged. Only English-language publications were considered, which may have excluded relevant data in other languages. The review was also restricted to in vitro experimental studies, which, while necessary for the focused research question, prevents the inclusion of clinical outcomes that would strengthen the evidence base. Furthermore, heterogeneity in methodologies and outcome measures precluded meta-analysis and results were synthesized qualitatively. The limited reporting of randomization and absence of blinding further reduce confidence in the comparative findings and warrant cautious interpretation. Given the small number of included studies, formal assessment of publication bias was not considered meaningful; therefore, publication bias and selective reporting cannot be excluded. In addition, similarities in materials, manufacturers, or laboratory workflows across some studies may limit the independence and technological diversity of the available evidence.

Implications for Practice and Future Perspectives

Within the limits of the current evidence, AM appears to be a promising alternative to SM for inlay and onlay fabrication, offering comparable adaptation and enhanced precision. Nevertheless, milling still provides excellent accuracy with certain materials, such as zirconia and hybrid ceramics.

For clinical practice, these findings suggest potential clinical applicability of 3D printing for inlay and onlay fabrication; however, routine clinical equivalence or superiority cannot be established from the current in vitro evidence.

For policy and research, the results highlight the importance of establishing standardized protocols for measuring adaptation and accuracy of indirect restorations. Standardized definitions and measurement protocols should also be adopted for MG, IG, trueness and precision to improve comparability among future studies. Future investigations should prioritize adequately powered designs, operator blinding and calibration procedures to reduce bias. Clinical studies are particularly needed to evaluate performance under functional loading and aging conditions. Comparative cost-effectiveness and chairside applicability of AM versus SM workflows should also be addressed, as these factors will ultimately determine the integration of 3D printing into routine restorative practice.

CONCLUSION

Within the limitations of this systematic review of in vitro studies, additive manufacturing appeared to have marginal and internal adaptation broadly comparable to subtractive milling under selected laboratory conditions, although results varied according to material, workflow and measurement method. Trueness favored certain milled materials in selected comparisons, whereas the limited evidence on precision and reproducibility favored AM. The available evidence does not establish clinical equivalence or superiority and confidence in these findings is limited by methodological heterogeneity and risk of bias. Future studies should adopt standardized outcome definitions and measurement protocols and include adequately powered clinical investigations assessing long-term performance.

Data Availability

All data analyzed during this study are included in this article and its supplementary files.

Author Contributions

Methodology development: ASK, RSA; Literature search: ASK, RSA; Data extraction: ASK, RSA; Quality assessment and data analysis: ASK, RSA, AD, AS, AAlt, AAlk, RA, NA, SA, MR, AAbd; Writing-original draft: ASK, RSA, AD, AS, AAlt, AAlk, RA, NA, SA, MR, AAbd; Writing - review and editing: ASK, RSA, AD, AS, AAlt, AAlk, RA, NA, SA, MR, AAbd; Project administration: ASK, RSA. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no competing interests.

Ethical Statement

Ethical approval was not required because this systematic review involved only previously published data and no human participants, identifiable patient information, or medical records, in accordance with applicable institutional requirements.

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Supplementary information

Supplementary file 1: Excluded studies and their reasons for exclusion

Supplementary file 2: QUIN assessment for included studies

Supplementary file 3: PRISMA 2020 checklist

Abbreviations

3D	Three-dimensional
AM	Additive manufacturing
SM	Subtractive manufacturing
CAD/CAM	Computer-aided design / computer-aided manufacturing
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
DLP	Digital light processing
SLA	Stereolithography
LCD	Liquid crystal display
MG	Marginal gap
IG	Internal gap
AMD	Absolute marginal discrepancy
OD	Overall discrepancy
QUIN	Quality Assessment Tool for In Vitro Studies
micro-CT	Micro-computed tomography
CBCT	Cone beam computed tomography
RMS	Root mean square deviation
TOR	Total overlap ratio
µm	Micrometer

Supplementary File 1: List of Excluded Studies and their Reasons for Exclusion

Study	Reason for exclusion	Reference
Noh <i>et al.</i>	Focused on restorations other than inlays/onlays	Noh <i>et al. Biomimetics</i> . 2025;10(1):67. doi:10.3390/biomimetics10010067
Igreţ <i>et al.</i>	Focused on restorations other than inlays/onlays	Igreţ <i>et al. Med Pharm Rep</i> . 2023;96(3):298–304. doi:10.15386/mpr-2588
Németh <i>et al.</i>	Ineligible study design	Németh <i>et al. J Dent</i> . 2025;153:105527. doi:10.1016/j.jdent.2024.105527

Supplementary File 2: Detailed QUIN Assessment for Included Studies Ahlholm *et al.* [27]

QUIN domain (0–2)	Judgment	Justification with in-text evidence
1) Clearly stated aim/objective	2	The Purpose/Aim is explicitly stated in the abstract and reiterated in the intro: to "evaluate and compare the accuracy of 3D printing versus CAD/CAM milling in the fabrication of inlay/onlay restorations."
2) Sample size calculation/justification	0	No a priori sample size calculation is reported; study labeled a pilot with six teeth.
3) Sampling technique (source, selection, criteria)	1	Teeth were "randomly collected" extracted molars; disinfection/storage described, but no detailed inclusion/exclusion criteria beyond type and preparation.
4) Comparison/control group	2	Direct head-to-head comparison of milled (M) vs 3D-printed (3D) restorations from the same digital impression/CAD for each tooth.
5) Methodology details/standardization	2	Extensive procedural detail: preparation per CEREC guidelines, scanner/software versions, printer model, resin, layer thickness, milling unit/blocks, micro-CT scan settings (kVp, voxel ~7 µm), replica protocol, repeated measures.

6) Operator details/calibration	1	Preparation attributed to an experienced clinician (stated in Discussion); however, operator number/training/calibration not systematically described in Methods.
7) Randomization (group allocation)	0	Allocation not applicable: paired design—each tooth produced both M and 3D restorations from the same CAD data (no between-specimen allocation).
8) Outcome measurement method (validity/reliability)	2	Methods and rationale well described: micro-CT linear gap measures at defined points (5 repeats each) + replica for average internal fit; micro-CT chosen for micrometer-scale resolution and supported by literature.
9) Outcome assessor details/calibration	0	Who performed the measurements and whether assessors were trained/calibrated is not specified.
10) Blinding (operator/assessor/statistician)	0	No blinding is reported for specimen preparation, measurement, or analysis.
11) Statistical analysis (appropriateness/reporting)	2	Wilcoxon signed-rank test, $\alpha=0.05$, SPSS v21.0 reported; results include means, SDs, and p-values (Table/figures).
12) Presentation of results (completeness/clarity)	2	Clear tables/figures with site-specific MG/IG (μm), replica data, and narrative summary of significance.

Final QUIN %: $(14 \div 22) \times 100 = 63.6$; Quality grade: Medium risk of bias

Lim *et al.* [28]

QUIN domain (0–2)	Score	Justification with article reference
1. Clearly stated aim/objective	2	The abstract states: “Objective: This article compares and evaluates the marginal and internal fitness and 3D accuracy of class II inlays fabricated using Tescera, milling of hybrid and zirconia blocks, and 3D printing with NextDent C&B.”
2. Sample size calculation/justification	0	No mention of a priori sample size calculation; groups of $n=13$ each were used without justification
3. Sampling technique	1	Resin tooth (Nissin) prepared into standardized cavity, then replicated into 52 master dies; however, no inclusion/exclusion criteria beyond resin model described
4. Comparison/control group	2	Four groups compared: conventional (TS), milled (LU, ZR), and 3D printed (NextDent C&B), serving as comparators
5. Methodology details/standardization	2	Detailed preparation of cavity, impression materials, stone dies, CAD design parameters (cement space $30 \mu\text{m}$), milling and printing devices, sintering protocol, and curing conditions provided
6. Operator details/calibration	0	No information on operator identity, training, or calibration for specimen preparation or measurement
7. Randomization	0	No random allocation process for specimens to groups is reported; groups predetermined by fabrication method
8. Outcome measurement method	2	Replica method for MG/IG with 6 measurement points under digital microscope, and trueness/precision assessed using 3D software (Geomagic Verify) following ISO 5725-1 standard
9. Outcome assessor details/calibration	0	The article does not specify who performed the measurements or if calibration/reliability was ensured
10. Blinding	0	No mention of blinding of operators, assessors, or statisticians
11. Statistical analysis	2	Statistical plan detailed: t-test, one-way ANOVA, two-way ANOVA, Duncan’s post hoc, $\alpha=0.05$; SPSS ver. 20.0 reported
12. Presentation of results	2	Results presented clearly with tables (marginal, internal, trueness, precision), figures (measurement points, 3D deviation maps), and proper statistical annotations

Final QUIN %: $(13 \div 24) \times 100 = 54\%$; Quality grade: Medium risk of bias

Pasha *et al.* [29]

QUIN domain (0–2)	Score	Justification with article reference
1) Clearly stated aim/objective	2	The abstract specifies the objective to evaluate internal adaptation and marginal fit of onlays made by CAD-CAM vs 3D printing using stereomicroscope and micro-CT.
2) Sample size calculation/justification	0	No a priori sample size calculation or justification is reported (20 teeth total; two groups of 10).
3) Sampling technique (source/criteria)	1	Materials & Methods: “20 extracted mandibular first molars without caries were selected”; basic prep standardization is described, but no detailed inclusion/exclusion or selection method.
4) Comparison/control group	2	Two-arm head-to-head comparison: CAD-CAM (milled zirconia) vs 3D-printed resin onlays from digital impressions.
5) Methodology details/standardization	2	Extensive procedural details: standardized onlay prep (dimensions, burs), digital scanning (Shining 3D), CAD/CAM and printing workflows, materials named, replica technique steps, stereomicroscope settings, and micro-CT acquisition.
6) Operator details/calibration	0	Operator identity/training/calibration for preparation and measurements not reported.
7) Randomization (allocation to groups)	0	Specimens were “divided into two groups” but no random sequence generation/allocation concealment is described.
8) Outcome measurement method (validity/reliability)	2	Methods clearly defined: replica per Molin & Karlsson with stereomicroscope (20 $\times$) at specified sites, and micro-CT (GE X-ray) with rationale for precision/non-destructive assessment.
9) Outcome assessor details/calibration	0	Who measured and whether assessors were trained/calibrated is not stated.
10) Blinding (operator/assessor/statistician)	0	No blinding reported for specimen prep, measurement, or analysis.
11) Statistical analysis (appropriateness/reporting)	2	Independent Student’s t-test reported with means $\pm$ SD, p-values and site-wise comparisons; data summarized in Tables 1–2.
12) Presentation of results (completeness/clarity)	2	Clear presentation: tables for replica and micro-CT outcomes, figures for imaging, and explicit statement of significant differences at each site.

Final QUIN %: $(13 \div 24) \times 100 = 54\%$; Quality grade: Medium risk of bias

Cantó-Navés *et al.* [30]

QUIN domain (0–2)	Score	Justification with article reference (section/table/figure)
1) Clearly stated aim/objective	2	Objective stated in Abstract and reiterated in Introduction: to compare the internal and marginal adaptation of printed vs milled onlays using a standardized digital workflow.
2) Sample size calculation/justification	0	No a priori sample-size calculation or power analysis reported; groups fixed at n=22 each (see Materials and Methods – Sample size/Groups).
3) Sampling technique (source/criteria)	1	Single standardized resin molar preparation used; onlays fabricated from the same CAD file (Methods – Tooth model and preparation). No explicit inclusion/exclusion criteria beyond model description.
4) Comparison/control group	2	Direct head-to-head comparison: milled (VHF K5+) vs SLA-printed (Form 3+) onlays from identical CAD (Methods – Fabrication procedures).
5) Methodology details/standardization	2	Detailed protocols: prep geometry, CAD settings, milling/printing parameters (50 µm layers, IPA wash, post-cure 2x20 min at 60 °C), scanner (Medit T500), alignment software, and analysis pipeline (Limaguide 1.9.1) (Methods – Manufacturing & Measurement workflow).
6) Operator details/calibration	0	The article does not report operator identity/number, training, or calibration for fabrication or measurements (Methods: no operator details).
7) Randomization (allocation)	0	No statement of random allocation of specimens to groups; groups defined by fabrication method (Methods – Grouping).
8) Outcome measurement method (validity/reliability)	2	Triple-scan digital superimposition described stepwise; two orthogonal section planes defined via reference spheres; points A–N mapped; rationale and repeatable pipeline given (Methods – Digital measurement protocol; Figure showing reference planes/points).
9) Outcome assessor details/calibration	0	No information on who performed the measurements or assessor calibration/repeatability (Methods/Results: not reported).
10) Blinding (operator/assessor/statistician)	0	No blinding reported for fabrication, measurements, or analysis (Methods: absent).
11) Statistical analysis (appropriateness/reporting)	2	Two-way ANOVA (Type × Location) reported with p-values; interaction stated ns; post-hoc comparisons where applicable; results summarized numerically (Statistics subsection; Results with p-values).
12) Presentation of results (completeness/clarity)	2	Clear tables of marginal, internal, central gaps (µm, mean ± SD) and statement that printed < milled at all sites; variability discussed (Results; Tables; Figure of measurement scheme).

Final QUIN %: $(13 \div 24) \times 100 = 54\%$; Quality grade: Medium risk of bias

Peskersoy and Oguzhan [31]

QUIN domain (0–2)	Score	Justification with article reference (section/table/figure)
1) Clearly stated aim/objective	2	The Abstract/Introduction state the aim: to compare marginal fit and bond strength of onlay restorations made by 3D printing, CAD/CAM, and conventional methods.
2) Sample size calculation / justification	0	No a priori sample-size calculation or power analysis reported; the study uses n=60 molars divided into three groups without justification.
3) Sampling technique (source/criteria)	1	Caries-free extracted mandibular first molars (n=60); storage, embedding, and standardized preparation described, but no detailed inclusion/exclusion beyond “caries-free” or recruitment method.
4) Comparison / control group	2	Three comparators specified: 3D printing (AM), CAD/CAM milling (CS/SM), and conventional indirect composite (SG).
5) Methodology details / standardization	2	Extensive, reproducible protocols: prep geometry & dimensions, scanners, CAD/CAM/printing parameters (Vaseo XS, 405 nm, 50 µm; Otofash 1500+1500 flashes), milling settings (CAMcube M10), cementation protocol, and micro-CT settings (SCANCO µCT 50; 20 µm slice; 90 kV).
6) Operator details / calibration	1	Preparations performed by the same dentist (operator consistency), but no training/calibration or number of outcome assessors reported.
7) Randomization (allocation)	1	Teeth were “randomly divided into three groups” (AM/CS/SG), but no description of sequence generation or allocation concealment.
8) Outcome measurement method (validity/reliability)	2	Micro-CT described as a non-invasive, objective method; regions defined (occlusal, middle-third, cervical), sectioning strategy and calibration approach outlined; void analysis (BV/TV; 3D reconstruction). Microshear bond strength test protocol detailed.
9) Outcome assessor details / calibration	0	Who performed measurements and whether assessor calibration/repeatability was performed is not specified.
10) Blinding (operator/assessor/statistician)	0	No blinding reported for specimen preparation, outcome measurement, or data analysis.
11) Statistical analysis (appropriateness/reporting)	2	ANOVA with Tukey, t-tests, and chi-square; $\alpha=0.05$ reported; significance stated for each outcome (Tables/Figures).
12) Presentation of results (completeness/clarity)	2	Clear tabulation/figures: Table 1 (marginal gaps), Table 2 (bond strength pre/post 5000 TC), Figures 4–9 (regional gaps, voids, BV/TV). Results interpreted against <120 µm clinical threshold.

Final QUIN %: $(15 \div 24) \times 100 = 62.5\%$; Quality grade: Medium risk of bias

Özden and Uygun [32]

QUIN domain (0–2)	Score	Justification with article reference
1) Clearly stated aim/objective	2	Abstract/Introduction: “The aim of this study was to evaluate the trueness of 3D-printed dental inlays fabricated using different permanent dental resins and subjected to distinct postcuring times.”

2) Sample size calculation / justification	2	Materials & Methods: Sample size determined using G*Power 3.1.97 for 80% power, $\alpha=0.05$, effect size 0.30; minimum $n=20$ per group justified. 180 inlays fabricated ($n=20$ per subgroup).
3) Sampling technique (source/criteria)	1	Reference tooth: mandibular phantom molar scanned, standardized inlay prep designed in Ansys SpaceClaim, duplicated for all groups. No biological teeth used, so no inclusion/exclusion criteria apply.
4) Comparison/control group	2	Three resin types (Senertek, Crowntec, Bego) $\times$ three postcuring times (2000, 4000, 6000 flashes), creating nine groups; direct comparison possible.
5) Methodology details / standardization	2	Comprehensive: CAD design dimensions (10° convergence, 2 mm depth), STL slicing in Chitubox, LCD printer settings (Phrozen Sonic Mini 8K, 50 μ m layers), IPA cleaning protocols, Otofash G171 nitrogen-curing.
6) Operator details / calibration	2	Reported: “the same researcher (YÖ) rescanned 10% of the specimens and resuperimposed them after two weeks”; calibration assessed with intraclass correlation coefficients for repeatability.
7) Randomization (allocation)	1	Groups “divided” into subgroups of 20; no description of randomization process beyond equal assignment.
8) Outcome measurement method (validity/reliability)	2	Trueness measured using Geomagic Control X, best-fit superimposition, RMS and TOR outputs per ISO 12836 standards. Methodology follows international norms.
9) Outcome assessor details / calibration	2	Same operator (YÖ) did repeat scanning and superimposition, with repeatability verified via ICCs, ensuring assessor calibration.
10) Blinding (operator/assessor/statistician)	0	No mention of blinding of operator, assessor, or statistician. ozden and oygun2025
11) Statistical analysis (appropriateness/reporting)	2	SPSS v24.0 used; Shapiro–Wilk normality; MANOVA and Tukey HSD post hoc; p-values clearly reported (Tables 2–4, Figs. 3–4).
12) Presentation of results (completeness/clarity)	2	Results presented in Tables 2–4 (RMS/TOR means $\pm$ SDs), Figures 3–4 (MANOVA plots); discussion relates outcomes to clinical thresholds.

Final QUIN %: 75%; Quality grade: Low risk of bias

Daghrery *et al.* [33]

QUIN domain (0–2)	Score	Justification with article reference
1) Clearly stated aim/objective	2	The study aimed “to compare the absolute marginal discrepancy (AMD), marginal gap (MG), internal gap (IG), and overall discrepancy (OD) of 3D-printed, milled and conventional inlays.” (Introduction / Aim).
2) Sample size calculation/justification	2	A priori calculation with G*Power 3.1.9.7: power = 0.99, $\alpha = 0.05$, effect size $f = 5.000791$; minimum $n=6$ /group rounded to $n=10$ allowing 40% failure. (Materials & Methods — Sample size).
3) Sampling technique (source/selection)	2	A standardized Class II MOD typodont tooth was prepared; 40 resin dies were digitally replicated from this preparation (single CAD source), specifying scanner, printer, die material and post-cure. (Materials & Methods — Tooth preparation for inlay; Resin dies).
4) Comparison/control group	2	Four groups defined and compared: PVC (printed Crownplus), PVT (printed TriniQ), MVE (milled Vita Enamic), and CGP (conventional Gradia Plus, control). (Materials & Methods — Randomization; Table 1).
5) Methodology details/standardization	2	Comprehensive workflow: digital impressions; cement spacer 40 μ m (1 mm from margins); printer/milling settings; post-curing; CBCT parameters and sectioning protocol. (Materials & Methods — Digital workflow; Groups; Measurement of discrepancies).
6) Operator details/calibration	1	Measurements performed by a single examiner with 10 years’ CBCT experience; operator/assessor calibration procedures not reported. (Materials & Methods — Measurement of discrepancies).
7) Randomization (allocation)	1	Dies were “randomly divided into four groups of 10 each”; sequence generation/allocation concealment not described. (Materials & Methods — Randomization).
8) Outcome measurement method (validity/reliability)	2	Detailed CBCT-based linear gap protocol across MD/BL sections with predefined points; AMD, MG, IG, OD computed from 69 measurements per sample; software specified. (Materials & Methods — Measurement of discrepancies; Figs 2–3).
9) Outcome assessor details/calibration	1	Assessor identity and experience reported (single examiner, 10 years CBCT); formal calibration/repeatability metrics not provided. (Materials & Methods — Measurement of discrepancies).
10) Blinding (operator/assessor/statistician)	0	No blinding reported for fabrication, measurements, or analysis. (No statement of blinding in Methods/Results).
11) Statistical analysis (appropriateness/reporting)	2	IBM SPSS 29; one-way ANOVA with Tukey for AMD/MG/IG/OD; Pearson correlations; significance level stated; group-wise results tabulated. (Materials & Methods — Statistical analysis; Results; Table 2–3).
12) Presentation of results (completeness/clarity)	2	Outcomes presented as mean $\pm$ SD (mm) with figures/tables (Table 2 for overall; Table 3 for margins; Figs 4–6; Supplementary Tables S1–S2). (Results).

Final QUIN %: $(19 / 24) \times 100 = 79.2\%$; Quality grade: Low risk of bias

Supplementary File 3: PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Title, Abstract
ABSTRACT			

Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Abstract, attached below
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Background
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Abstract (Objective); Background (end)
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Methods: Eligibility Criteria
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Methods: Information sources
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Table 1; Methods: Information sources
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Methods: Study selection
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Methods: Data extraction
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Methods: Eligibility criteria; Data extraction
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Methods: Data extraction
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Methods: Risk of bias assessment; Table 3
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Results: Study selection; Fig 1
Study characteristics	17	Cite each included study and present its characteristics.	Results: Study characteristics; Table 2
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Results: Risk of bias within studies; Table 3
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Results: Results of individual studies and main findings; Table 2; Table 4
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Discussion
	23b	Discuss any limitations of the evidence included in the review.	Discussion: Limitations
	23c	Discuss any limitations of the review processes used.	Discussion: Limitations
	23d	Discuss implications of the results for practice, policy, and future research.	Implications for practice and future perspectives
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	Methods: Protocol and registration
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Methods: Protocol and registration
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	Not applicable
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Funding statement

Competing interests	26	Declare any competing interests of review authors.	Competing Interests
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Data Availability

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 2021;372:n71. doi: 10.1136/bmj.n71. This work is licensed under CC BY 4.0. To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>