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Accuracy and retention of laminate veneers made from zirconia, resin composite, and lithium disilicate using additive and subtractive techniques: An in vitro study

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ABSTRACT

Objectives: To evaluate and compare the trueness and retention of laminate veneers (LVs) fabricated using four different CAD-CAM material-process combinations, including both additive (AM) and subtractive (SM) manufacturing techniques.
Methods: An in vitro study was conducted using a standardized maxillary central incisor preparation. Eighty LVs were fabricated (n=20/group) from: AM resin composite (AM-RC), AM zirconia (AM-Z), SM advanced lithium disilicate (SM-LDS), and SM zirconia (SM-Z). Trueness was assessed using root mean square (RMS) deviation values and color map visualization. Retention was tested after thermomechanical aging. One-way ANOVA and Tukey's HSD test were used for statistical analysis (α=0.05).
Results: There were significant differences in trueness and retention among groups ($p<0.005$). AM-RC showed the highest RMS values (e.g., internal: 38.32 ±2.2 μm) and the lowest retention (689.85 ±30.81 N). No significant differences in trueness or retention were found between SM-Z (internal: 30.12 ±2.4 μm; 782.10 ±34.12 N), SM-LDS (internal: 31.85 ±2.3 μm; 801.90 ±39.43 N), and AM-Z (internal: 32.45 ±2.5 μm; 799.45 ±33.83 N).
Conclusions: The material type and manufacturing method significantly influenced the adaptation and retention of LVs. AM-Z, SM-Z, and SM-LDS demonstrated comparable and clinically acceptable outcomes, while AM-RC showed inferior trueness and retention.
Clinical Relevance: Subtractive lithium disilicate and zirconia, as well as high-performance additive zirconia, exhibited clinically acceptable adaptation and retention, supporting their use in definitive laminate veneers. In contrast, printed resin composite showed inferior performance and should be limited to provisional applications.

1. Introduction

Laminate veneers (LVs) are widely used in restorative dentistry due to their minimally invasive approach and esthetic potential in addressing issues such as discoloration, minor fractures, malposition, or wear in anterior teeth [1,2]. A range of materials has been employed in their fabrication, including feldspathic porcelain, leucite-reinforced ceramics, lithium disilicate (LDS), resin composites, and zirconia [3]. Each material presents distinct advantages and limitations in terms of optical, mechanical, and adhesive properties, which can influence clinical outcomes [4].

The introduction of computer-aided design and manufacturing (CAD-CAM) technologies has revolutionized dental prosthetics and materials, offering both subtractive manufacturing (SM) and 3D-

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printing or additive manufacturing (AM) workflows [5–12]. SM is well established, delivering consistent precision, particularly when using LDS or zirconia ceramics [13,14]. However, it involves significant material waste and tool wear and may face limitations in fabricating restorations with very thin geometries due to the dimensions and constraints of milling burs [10,11,15]. AM has emerged as an alternative that enables efficient material usage, minimal wastage, and greater design freedom, particularly for fabricating restorations with complex geometries and thinner thicknesses without the risk of micro-sized cracks [5,10,11,16]. However, AM methods are still under evaluation due to potential concerns regarding dimensional accuracy, material uniformity, and long-term clinical performance [17].

In the context of CAD-CAM materials, LDS is commonly preferred for SM workflows due to its high flexural strength, translucency, and favorable aesthetic outcomes [18]. Due to its brittleness, LDS is milled in a partially crystallized "blue" stage to facilitate machining; however, the process can introduce surface and subsurface defects, such as chipping and microcracks, which may persist after crystallization but can be partially reduced through polishing, extended heat treatment, or adhesive luting [19]. Among the newly developed materials enabled by advances in CAD-CAM technology is the SM advanced LDS ceramic. This material exhibits reduced crystallization time and enhanced mechanical strength compared to conventional LDS, owing to its zirconia-reinforced crystal phase and optimized microstructure [20]. On the other hand, AM workflows have led to the introduction of printable resin-based materials, such as urethane acrylate, resin composites, and ceramic-filled hybrid resin composites, as well as ceramic suspensions such as 3 mol % yttria-stabilized tetragonal zirconia polycrystals (3Y-TZP) [5,9–11]. Lithography-based ceramic manufacturing (LCM), a high-precision AM technique that uses a specialized slurry, which is a mixture of ceramic powder suspended in a photosensitive resin matrix [9,11,12,21], enabling the fabrication of ceramic restorations with fine thicknesses [22], high accuracy and good tensile bond strength [9,11,12]. Nevertheless, it requires careful post-processing, including debinding and sintering, which may introduce dimensional changes [17,23]. In addition, resin-based LVs are considered a viable alternative to SM resin composite veneers, with reported outcomes of similar or higher trueness and a lower risk of caries progression [10,24].

Achieving optimal outcomes in LVs hinges on various factors, including durability, fabrication accuracy, marginal and internal fit, mechanical and bonding strength, esthetics, and color stability [3, 25–28]. Despite the increasing use of both technologies, limited evidence is available comparing the performance of LVs fabricated through AM versus SM methods. Most existing research has focused on complete crowns [6,7,12,29–46] or indirect partial restorations [5,47,48], with little emphasis on the thin, aesthetically critical LVs [5,10,49–51]. Considering the thinner geometry of veneers and their dependency on internal and marginal adaptation for bonding success and longevity, understanding how different fabrication methods and materials affect trueness and retention is essential.

Given the current lack of comparative data on AM and SM fabrication techniques for LVs, particularly involving advanced materials, the present study aimed to evaluate and compare the trueness and retention of LVs fabricated using four different material-process combinations: AM resin composite, AM zirconia, SM lithium disilicate, and SM zirconia. The null hypothesis was that there would be no significant differences in fabrication trueness or retention among LVs fabricated using different materials and manufacturing techniques.

2. Materials and methods

This was an in vitro study; no human or biological samples were used, and ethical approval was not required. A laminate veneer preparation was performed on a maxillary right central incisor tooth from an operative jaw model (Nissin Dental Products Inc., Kyoto, Japan). Tooth preparation was standardized by uniformly reducing 0.7 mm from the labial surface, 1.0 mm from the proximal surfaces, and 1.5 mm from the incisal edge. A chamfer finish line was prepared on the gingival and proximal surfaces, and a butt joint configuration was used at the incisal edge. The tooth was scanned using an intraoral scanner (TRIOS 3; 3Shape A/S, Copenhagen, Denmark), and the data were exported in standard tessellation language (STL) format (MD-STL).

Eighty resin dies were fabricated from the MD-STL using a digital light processing (DLP) 3D printer (MAX UV; Asiga, Sydney, Australia) and photopolymerized resin (VeriModel OS Ivory; Whip Mix Corp., Louisville, KY, USA). The same MD-STL was used to design LVs in dedicated software (TRIOS Design Studio; 3Shape A/S), with a 25-μm cement space and a restoration thickness of 0.7 mm [52] (Figs. 1a-c). The resulting design file (RLV-STL) was used to fabricate 80 LVs ($n = 20$ per group) from four different materials: (1) SM-RC, additively manufactured glass filler-reinforced resin composite (Crowntec, VOCO GmbH, Cuxhaven, Germany); (2) AM-Z, additively manufactured 3 mol % yttria-stabilized zirconia (3Y-TZP, LithaCon 3Y 210; Lithoz GmbH, Vienna, Austria); (3) SM-LDS, subtractively manufactured advanced LDS (CEREC Tessera; Dentsply Sirona, Bensheim, Germany); and (4) SM-Z, subtractively manufactured translucent zirconia (Katana UTML; Kuraray Noritake Dental Inc., Tokyo, Japan). The SM-LDS group, representing a well-established clinical standard, was considered the reference group for comparative analyses [53].

For the AM-RC group, veneers were printed using a 50-μm layer thickness and vertical orientation with the same DLP printer. Post-processing involved ethanol cleaning using lint-free cloths (Ethanol Absolut; Dr. Grogg Chemie AG) [6,54], followed by 10 min of air drying, and post-polymerization with a xenon light-flash device (Otoflash G171; NK Optik GmbH, Baierbrunn, Germany), which delivered 2000 flashes per surface in a nitrogen gas atmosphere [6,7].

For the AM-Z group, lithography-based ceramic manufacturing (LCM) technology (CeraFab System S65 Medical; Lithoz GmbH) was employed. The RLV-STL was imported into the printer's nesting software, and the parts were arranged in a vertical orientation with a layer thickness of 25 μm [33]. After printing, veneers were detached from the build platform, the support structures were removed, and then they were cleaned in a cleaning fluid (LithaSol 20; Lithoz GmbH) using the manufacturer's dedicated cleaning system (CeraCleaning Station Ultra; Lithoz GmbH), then sintered in a high-temperature furnace (LHTCT 08/16; Nabertherm GmbH, Lilienthal, Germany) following manufacturer-recommended thermal cycles [33].

SM groups were milled using a four-axis CAD-CAM milling unit (CEREC Primemill; Dentsply Sirona). Milled specimens were ultrasonically cleaned in distilled water for 10 min (Eltrosonic Ultracleaner 07–08; Eltrosonic GmbH, Dusseldorf, Germany) and dried. SM-LDS veneers underwent crystallization in a ceramic furnace (Programat CS4; Ivoclar Vivadent AG, Schaan, Liechtenstein) at a peak temperature of 840 °C for 10 min, following the manufacturer's instructions. All veneers, regardless of material or fabrication method, were cleaned with steam, air-dried, and polished using P400, P800, and P1200 silicon carbide abrasive papers (CarbiMet PSA; Buehler, Lake Bluff, IL, USA) under water cooling [55].

The fabricated LVs (Figs. 1d and 1e) were scanned again using the same intraoral scanner under controlled ambient conditions. The resulting STL files (TLV-STL) were analyzed using 3D inspection software (Geomagic Control X 2022.3; 3D Systems Inc., Rock Hill, SC, USA). The reference file (RLV-STL) was imported, segmented into internal, external, and marginal surfaces, and aligned with TLV-STLs using initial and best-fit alignments [11]. Root mean square (RMS) deviation values were calculated for each surface. A color map with nominal deviations of ±100 μm and a tolerance of ±10 μm was generated to visualize discrepancies. Lower RMS values were interpreted as higher fabrication trueness, following ISO 5725–2 guidelines [56].

For retention testing, resin dies were treated according to each material's bonding protocol. All dies were air-particle abraded with 50-μm aluminum oxide (Korox 50; Bego) at 0.2 MPa for 10 s and steam cleaned.

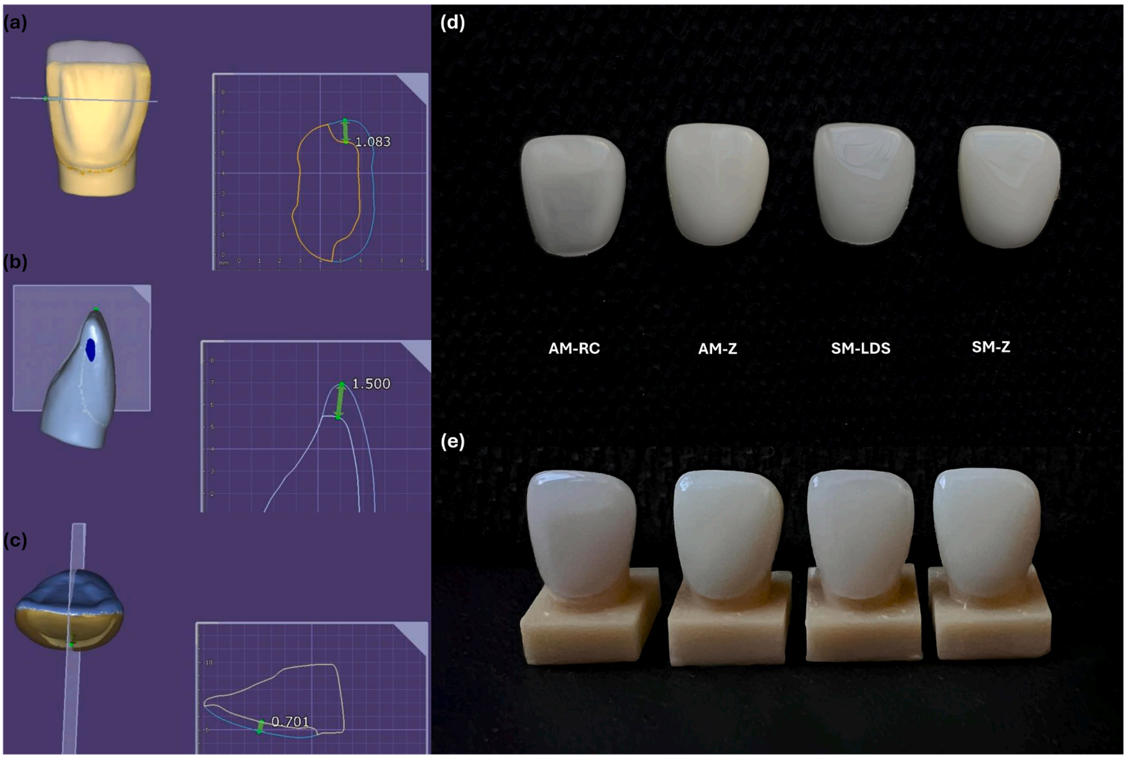

Fig. 1. (a) Proximal reduction of 1.0 mm and the corresponding laminate veneer thickness in that area; (b) incisal reduction of 1.5 mm and the corresponding laminate veneer thickness; (c) labial reduction of 0.7 mm and the corresponding laminate veneer thickness; (d) fabricated specimens from each material group; and (e) specimens mounted on their corresponding resin dies. AM-RC: additively manufactured, glass filler-reinforced resin composite; AM-Z: additively manufactured zirconia (3 mol % yttria-stabilized tetragonal zirconia polycrystals); SM-LDS: subtractively manufactured, advanced lithium disilicate; SM-Z: subtractively manufactured translucent zirconia.

SM-LDS veneers were etched with 4 % hydrofluoric acid (IPS Ceramic Etching Gel; Ivoclar AG) for 20 s, rinsed for 10 s, air-dried, and treated with ceramic primer (Clearfil Ceramic Primer Plus; Kuraray Noritake) for 60 s. AM and SM zirconia and AM-RC veneers were also air-abraded and treated with the same ceramic primer for 60 s. All veneers were cemented onto the dies using dual-cure adhesive resin cement (Panavia V5; Kuraray Noritake) and light polymerized for 40 s (Bluephase; Ivoclar AG) at 950 mW/cm^2. A brass jig applied constant 2-N pressure for 10 min during cementation [57]. Cemented specimens were stored in distilled water at 37 °C for 24 h.

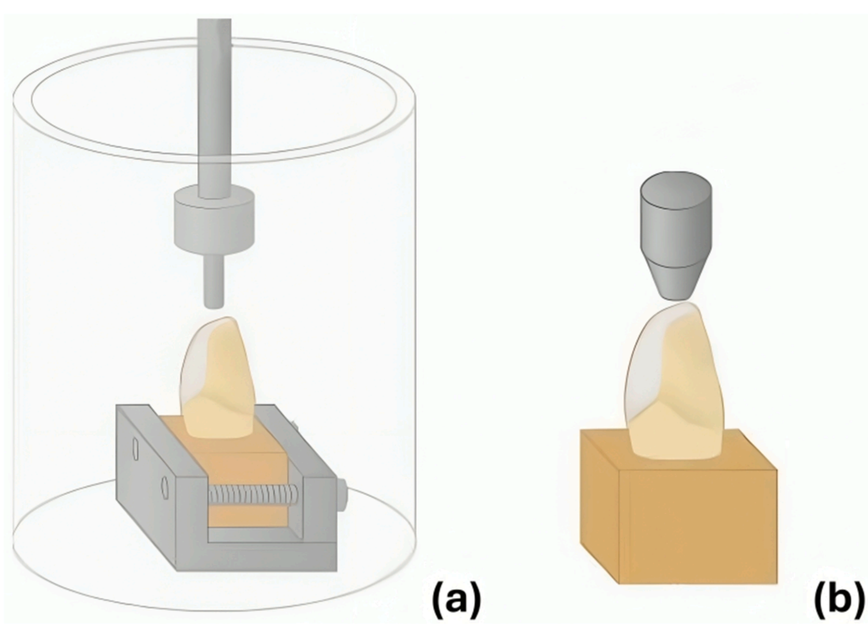

Fig. 2. Graphical illustration of the experimental workflow showing: (a) thermomechanical aging of laminate veneers mounted on resin dies in a chewing simulator, simulating clinical function through cyclic mechanical loading and thermal cycling; and (b) retention (detachment) testing setup using the universal testing machine, illustrating the custom fixture design, perpendicular load application at the incisal margin, and direction of force during debonding.

Thermomechanical aging was performed using a chewing simulator (CS-4.8; SD Mechatronik, Feldkirchen-Westerham, Germany) at 49 N load and 1.2 Hz frequency for five million cycles (Fig. 2a), simulating approximately 20 years of clinical function [58]. The simulator generated horizontal and vertical displacements of 1 mm and 2 mm, respectively, to mimic masticatory movements. Thermal cycling was conducted in parallel, alternating between 5 °C and 55 °C water baths with 30-second dwell times and 10-second transfer times between baths, for a total of 54,825 cycles. After aging, the veneers were examined under a stereomicroscope (M420; Leica Microsystems, Wetzlar, Germany) for signs of failure. Specimens were then mounted on a universal testing machine (ZwickRoell; ZwickRoell AG, Ulm, Germany). A tensile pull-off load was applied axially along the path of insertion, contacting the incisal margin via a stainless-steel flat-ended indenter, at a crosshead speed of 1 mm/min until debonding occurred (Fig. 2b). The maximum load required to dislodge each veneer was recorded in newtons (N) using testXpert III software (ZwickRoell AG) [58]. Thermomechanical aging, thermocycling, and retention testing were performed sequentially on the same specimens to simulate cumulative intraoral conditions.

An a priori power analysis for one-way ANOVA (four groups, α=0.05, desired power=0.95) using an anticipated effect size of f = 0.623 indicated that a minimum of 12 specimens per group (48 total) was sufficient; therefore, 20 specimens per group (80 total) were included to enhance precision. Mean, standard deviation, and 95 % confidence interval (CI) values for RMS and retention were calculated. One-way ANOVA and Tukey's HSD test were used to assess differences among groups, with significance set at α=0.05.

3. Results

One-way analysis of variance revealed statistically significant differences in fabrication trueness (Fig. 3) across all tested veneer materials for external, internal, and marginal surfaces ($p < 0.005$). Among the groups, the AM-RC veneers demonstrated the highest RMS deviation values ($p \leq 0.001$) across all surfaces (external: 35.41 ± 2.7 μm; internal: 38.32 ± 2.2 μm; marginal: 39.23 ± 2.03 μm), indicating the lowest trueness. In contrast, SM-Z veneers showed the lowest RMS values (external: 27.89 ± 2.0 μm; internal: 30.12 ± 2.4 μm; marginal: 27.63 ± 2.2 μm), although the difference was not statistically significant compared to SM-LDS ($p = 0.174$) (Table 1). No statistically significant difference was found between AM-Z and SM-LDS groups ($p = 0.086$).

The retention test also revealed significant differences among groups ($p < 0.005$). The AM-RC group exhibited the lowest retention force (689.85 ± 30.81 N), while SM-LDS and AM-Z showed higher but statistically similar values (SM-LDS: 801.90 ± 39.43 N; AM-Z: 799.45 ± 33.83 N; $p = 0.123$). SM-Z demonstrated slightly lower retention values than SM-LDS and AM-Z; however, the difference was not statistically significant ($p = 0.198$) (Table 2). In all groups, veneer dislodgment occurred during testing without catastrophic failure, and no visible fractures were observed under microscopic examination.

4. Discussion

Significant differences in fabrication trueness were detected across all evaluated surfaces of the LVs. AM-RC specimens exhibited the lowest external, internal, and marginal trueness and generated the weakest retention, whereas AM-Z, SM-LDS, and SM-Z demonstrated comparable accuracy and retention. Mean RMS deviation across groups did not exceed 50 μm, values that fall below the accepted clinical threshold [59]. Debonding forces ranging from 689 to 801 N significantly exceed the clinically accepted 500–600 N threshold required for ceramic restorations under functional loading [60–62]. Normal masticatory forces generally range from 200 to 540 N, with average values around 300 N, while parafunctional activities such as bruxism can generate peak forces up to 880 N [63,64]. Because manufacturing workflow and material composition produced statistically significant effects on both trueness and retention, the null hypothesis was rejected. The differences in trueness and retention can be explained by the intrinsic properties of the materials and the characteristics of the manufacturing techniques [17]. Subtractive milling of lithium disilicate and zirconia provides precise control and dimensional stability, resulting in high accuracy and retention. In contrast, additively manufactured resin composites showed greater deviations and lower retention, likely due to layer-by-layer polymerization and reduced mechanical stability [65,66]. Additively manufactured zirconia achieved comparable outcomes to subtractive groups, likely owing to optimized slurry-based lithography that improves dimensional accuracy [67].

Earlier investigations have reported substantial variability in the geometric accuracy of crowns, partial restorations, and veneers as a function of chemistry, build technology, and print parameters [5–7]. The inferior trueness observed for AM-RC may be explained by polymerization shrinkage of its methacrylate matrix combined with voxel

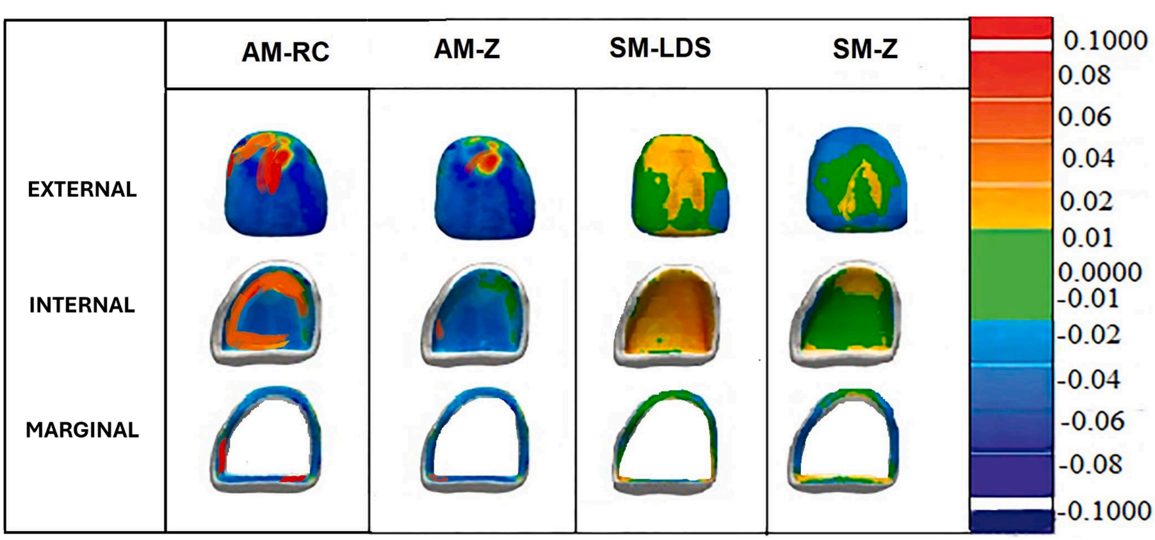

Fig. 3. Representative color map images showing deviation patterns on external, internal, and marginal surfaces of laminate veneers for each material group. Green indicates deviations within the tolerance range (±10 μm), red represents overcontour areas, and blue denotes undercontour areas (nominal deviation limits: ±100 μm). AM-RC: additively manufactured, glass filler-reinforced resin composite; AM-Z: additively manufactured zirconia (3 mol % yttria-stabilized tetragonal zirconia polycrystals); SM-LDS: subtractively manufactured, advanced lithium disilicate; SM-Z: subtractively manufactured translucent zirconia.

Table 1
Root mean square (RMS) deviation values (μm) of laminate veneers for each material group across external, internal, and marginal surfaces.

Groups ($n = 20$)	External		Internal		Marginal	
	(Mean ±SD)	[95 % CI]	(Mean ±SD)	[95 % CI]	(Mean ±SD)	[95 % CI]
AM-RC ($n = 20$)	35.41 ± 2.7^b	[34.15–36.67]	38.32 ± 2.2^b	[37.29–39.35]	39.23 ± 2.03^b	[38.28–40.18]
AM-Z ($n = 20$)	29.32 ± 2.2^a	[28.29–30.35]	33.41 ± 2.3^a	[32.33–34.49]	28.81 ± 2.1^a	[27.83–29.79]
SM-LDS ($n = 20$)	28.01 ± 1.9^a	[27.10–28.92]	29.32 ± 2.9^a	[28.00–30.64]	29.99 ± 2.5^a	[28.84–31.14]
SM-LDS ($n = 20$)	27.89 ± 2.0^a	[26.94–28.84]	30.12 ± 2.4^a	[29.02–31.22]	27.63 ± 2.2^a	[26.60–28.66]

Values are presented as mean ±standard deviation. Lower RMS values correspond to higher fabrication trueness. AM-RC: additively manufactured, glass filler-reinforced resin composite; AM-Z: additively manufactured zirconia (3 mol % yttria-stabilized tetragonal zirconia polycrystals); SM-LDS: subtractively manufactured, advanced lithium disilicate; SM-Z: subtractively manufactured translucent zirconia; SD: standard deviation; CI: confidence interval. Different superscript lowercase letters indicate statistically significant differences between surface regions within the same material group ($p < 0.05$).

Table 2
Mean retention forces (N) of laminate veneers fabricated using different CAD-CAM materials and techniques.

Group	Mean ±SD	SE	95 % CI for mean		Minimum	Maximum
			Lower	Upper		
AM-RC ($n = 20$)	689.85 ± 30.812^a	3.536	682.95	695.75	644	735
AM-Z ($n = 20$)	799.45 ± 33.834^b	2.646	791.91	806.99	748	851
SM-LDS ($n = 20$)	801.90 ± 39.430^b	2.780	795.08	807.72	743	861
SM-Z ($n = 20$)	720.52 ± 40.745^b	2.934	712.12	730.76	659	782

Values are presented as mean ±standard deviation (SD). Retention was measured as the maximum load (in newtons) required to debond each veneer after thermomechanical aging. AM-RC: additively manufactured, glass filler-reinforced resin composite; AM-Z: additively manufactured zirconia (3 mol % yttria-stabilized tetragonal zirconia polycrystals); SM-LDS: subtractively manufactured, advanced lithium disilicate; SM-Z: subtractively manufactured translucent zirconia; SD: standard deviation; SE: standard error; CI: confidence interval. Different superscript lowercase letters indicate statistically significant differences between groups for the same test parameter ($p < 0.05$).

anisotropy at a 50 μm layer height, a phenomenon documented to cause dimensional inaccuracy, uneven surfaces, and component warpage in vat-photopolymerization resins [65]. Although AM-Z also undergoes binder photopolymerization, subsequent debinding and sintering densification are anticipated by software-controlled oversizing, yielding deviation patterns dominated by slight yellow or red over-contouring chiefly on intaglio surfaces. SM-LDS presented predominantly green and occasional yellow areas, whereas SM-Z exhibited the most homogeneous green distribution, indicating the highest surface fidelity.

Trueness differences may also be attributed to disparities in layer thickness, particle distribution, and thermal behavior during processing [68]. AM-RC, with its thicker layers and higher organic content, is more susceptible to cumulative polymerization distortion, especially at fine margins or internal line angles [69,70]. In contrast, the fine-layer deposition used in AM-Z and the subtractive precision of SM-LDS and SM-Z allow for more accurate reproduction of complex anatomical details [17,33,51]. In LCM, the interplay of ceramic particle sedimentation, binder stability, and photopolymerization kinetics can affect green-state fidelity [71]. However, systematic oversizing and well-characterized sintering shrinkage curves could help compensate for these volumetric changes, particularly in AM-Z and SM-Z workflows [72]. Notably, SM-Z demonstrated exceptional consistency in surface geometry, a feature that may reflect both the intrinsic material homogeneity and the stability of the partially sintered pre-milled blanks used.

Findings concur with reports that inferior intaglio trueness compromises internal adaptation and may necessitate thicker cement layers prone to leakage and debonding [6,7]. However, published data on AM-RC remain contradictory: Molinero-Mourelle et al [6]. and Yılmaz et al [10]. documented superior accuracy for printed composites, likely attributable to differing resin formulations, preparation geometries, and build orientations. Anh et al [49]. likewise demonstrated that manufacturing technique influenced marginal adaptation when comparing milled and printed ceramic veneers. Orientation of support struts, resin viscosity, and post-processing protocols collectively influence geometric fidelity [73,74]. Supports placed at the incisal edge may induce warpage once detached, particularly in low-strength green bodies such as AM-RC [17]. Steam cleaning and silicon-carbide polishing might equalize minor asperities, potentially narrowing inter-group differences.

The distribution of retention followed a similar trend to trueness, with AM-RC presenting the lowest values. This observation can be attributed to its compromised intaglio accuracy, which results in non-uniform and excessively thick cement layers that may reduce micromechanical interlocking and increase the likelihood of cohesive failure within the luting agent [75]. Conversely, AM-Z, SM-LDS, and SM-Z demonstrated comparable retention, consistent with established bonding mechanisms for their respective material classes. This aligns with prior findings where bonding efficiency was highly dependent on material and surface preparation [76,77]. For zirconia-based materials, sandblasting followed by the application of MDP-containing primers facilitated a durable chemical interaction with the zirconia's oxide layer [78]. For LDS, hydrofluoric acid etching and silane coupling provided a stable and retentive interface through siloxane bonding [79]. These bonding protocols, supported by manufacturer recommendations and previous studies [11,77,80], contributed to consistent adhesion performance in the ceramic groups, even after thermomechanical loading. While all materials exceeded the average clinically relevant threshold of 300 N for retention [60,81], the reduced performance of AM-RC suggests its polymer matrix and limited bonding capacity under thermal and mechanical stress may still compromise long-term durability.

The present investigation provides one of the first comparative evaluations of laminate veneers fabricated using both additive and subtractive CAD-CAM workflows across four distinct material-process combinations (AM-RC, AM-Z, SM-LDS, and SM-Z) under standardized conditions. While previous studies have primarily focused on complete crowns or partial coverage restorations [47,48,82], limited evidence exists regarding laminate veneers, especially when evaluating different CAD-CAM technologies and material categories simultaneously. Additionally, most studies involving laminate veneers have focused on resin-based materials [10,52,83,84], whereas the current study integrates a broader range of materials, including zirconia and lithium disilicate. By combining RMS deviation analysis, detailed color mapping, and retention testing after long-term thermomechanical aging, this work establishes a comprehensive methodological framework that contributes to a better understanding of how manufacturing workflows and material selection affect the adaptation and retention of laminate veneers. In this study, a one-way ANOVA with Tukey's HSD post hoc test was used because the four groups represented predefined combinations of restorative material and manufacturing technique, analyzed as a single independent factor. A two-way ANOVA would have required evaluating material type and manufacturing technique as separate, independent variables with potential interaction effects, which was not applicable to the present study design.

All tested materials satisfied established criteria for surface accuracy ($<$50 μm) and debonding resistance ($>$300 N), indicating that AM-Z, SM-LDS, and SM-Z are suitable options for definitive veneers. The favorable performance of AM-Z supports integrating lithography-based ceramic manufacturing into chairside workflows, combining additive precision with reduced material waste. From a clinical perspective, material selection may also depend on cost, workflow efficiency, and accessibility. Subtractive lithium disilicate and zirconia are widely available and deliver predictable results but involve higher equipment costs and greater material waste. Additive zirconia achieves comparable accuracy with less waste but remains less accessible due to limited clinical adoption and higher system costs. Printed resin composites, while faster and more cost-effective, are currently better suited for provisional or low-stress indications until further advances. Future improvements may include optimizing the filler-to-resin ratio, enhancing the photopolymer chemistry to reduce volumetric shrinkage, increasing printing resolution, and refining post-processing protocols to improve interlayer fusion and minimize residual stresses, potentially leading to better adaptation and bonding performance.

In clinical scenarios with a normal stump shade and high esthetic demands, subtractively manufactured lithium disilicate veneers may be an appropriate choice. However, their inherent grayish undertone requires compensation through adequate restoration thickness and careful selection of resin cement shade to achieve optimal color outcomes. Conversely, in situations where the stump shade is darker and the patient also presents with zirconia-based posterior restorations, zirconia laminate veneers are preferable to ensure esthetic harmony across anterior and posterior regions in terms of color, translucency, and surface texture. These veneers can be fabricated either additively or subtractively, depending on clinical availability, workflow efficiency, and cost. In such cases, an advantageous preliminary step is the fabrication of additively manufactured resin composite veneers to serve as try-in restorations. This strategy avoids intraoral adjustments to definitive zirconia veneers at delivery, preserving their structural integrity and phase stability, while allowing the patient to preview the final esthetic outcome. Additionally, these AM resin veneers can function as provisional restorations, maintaining peri-gingival health and minimizing inflammation prior to definitive cementation. The high reproducibility of AM workflows further ensures that these provisional restorations are accurate replicas of the final design, thereby enhancing both clinical predictability and patient satisfaction. Looking forward, the ideal evolution of additive workflows will depend on two main fronts: (1) for AM resin composites, minimizing polymerization shrinkage, improving filler distribution, and developing more dimensionally stable photopolymer systems to enable their use in definitive veneers; and (2) for AM zirconia, refining slurry homogeneity, sintering protocols, and oversizing algorithms to achieve even greater accuracy, translucency, and mechanical reliability. In addition to these mechanical and structural advances, esthetic improvements are also crucial, including enhanced shade reproducibility, wider color availability, increased translucency gradients, and the possibility of multilayer or polychromatic printing to replicate natural tooth structures. Ultimately, what both clinicians and technicians seek is a digital workflow that allows the seamless fabrication of definitive veneers with maximum accuracy, reproducibility, esthetic integration, minimal material waste, and chairside efficiency—bringing additive manufacturing closer to becoming a routine option in daily prosthodontic practice.

A major limitation of this study is the use of standardized resin dies as bonding substrates. While this approach minimized variability and allowed for better standardization of preparation geometry, resin does not replicate the adhesive and biomechanical properties of natural enamel and dentin; hence, the results must be interpreted with caution. Furthermore, only a single preparation geometry, veneer thickness, and adhesive system were tested, and artificial aging was restricted to thermo-mechanical cycling. Future studies should include natural tooth substrates, varied preparation designs, alternative bonding protocols, and extended water storage.

5. Conclusions

Within the limitations of this in vitro study:

1. The restorative material and manufacturing technique significantly influenced the trueness and retention of laminate veneers.
2. Additively manufactured glass-filled resin composite veneers exhibited the highest surface deviations and the lowest bonding performance, suggesting their current use may be better suited for provisional or low-stress situations until further material and process optimizations are achieved.
3. Subtractively manufactured zirconia, subtractively manufactured lithium disilicate, and additively manufactured zirconia demonstrated comparable trueness and retention, supporting their suitability for definitive laminate veneers.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The data presented in this study will be made available on request from the corresponding author.

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CRediT authorship contribution statement

Rafat Sasany: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gülce Çakmak:** Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Seyed Ali Mosaddad:** Writing – review & editing, Visualization, Software, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] G. Guzman-Perez, C.A. Jurado, F. Azpiazu-Flores, K.I. Afrashtehfar, A. Tsujimoto, Minimally invasive laminate veneer therapy for maxillary central incisors, Medicina (Kaunas) 59 (2023) 603.
[2] S. Rinke, A.K. Pabel, X. Schulz, M. Rödiger, G. Schmalz, D. Ziebolz, Retrospective evaluation of extended heat-pressed ceramic veneers after a mean observational period of 7 years, J. Esthet. Restor. Dent. 30 (2018) 329–337.
[3] P. Klein, F.A. Spitznagel, A. Zembic, L.S. Prott, S. Pieralli, B. Bongaerts, M. I. Metzendorf, R. Langner, P.C. Gierthmuehlen, Survival and complication rates of feldspathic, leucite-reinforced, lithium disilicate and zirconia ceramic laminate veneers: a systematic review and meta-analysis, J. Esthet. Restor. Dent. 37 (2025) 601–619.
[4] S.M. Lee, Y.S. Choi, Effect of ceramic material and resin cement systems on the color stability of laminate veneers after accelerated aging, J. Prosthet. Dent. 120 (2018) 99–106.
[5] G. Çakmak, D. Steigmeier, M.E. Güven, D. Yilmaz, M. Schimmel, H.I. Yoon, B. Yilmaz, Fabrication trueness, intaglio surface adaptation, and marginal integrity of resin-based onlay restorations fabricated by additive and subtractive manufacturing, Int. J. Prosthodont. 37 (2024) 99–107.
[6] P. Molinero-Mourelle, A. Limones, M.E. Güven, M. Fonseca, A. Peutzfeldt, B. Yilmaz, G. Cakmak, Manufacturing accuracy, intaglio surface adaptation, and survival of additively and subtractively manufactured definitive resin crowns after cyclic loading: an in vitro study, Int. J. Prosthodont. 37 (2024) 175–185.
[7] G. Çakmak, A.M. Rusa, M.B. Donmez, C. Akay, Ç. Kahveci, M. Schimmel, B. Yilmaz, Trueness of crowns fabricated by using additively and subtractively manufactured resin-based CAD-CAM materials, J. Prosthet. Dent. 131 (2024) 951–958.
[8] R. Sasany, F.Z. Jamjoom, S.M. Uçar, B. Yilmaz, Nanoindentation creep: the impact of water and artificial saliva storage on milled and 3D-printed resin composites, J. Prosthodont. (2024).
[9] H. Nakai, M. Inokoshi, K. Nozaki, K. Komatsu, S. Kamijo, H. Liu, M. Shimizubata, S. Minakuchi, B. Van Meerbeek, J. Vleugels, F. Zhang, Additively manufactured Zirconia for dental applications, Materials (Basel) 14 (2021) 3694.
[10] D. Yılmaz, G. Çakmak, M.E. Güven, H.I. Yoon, M. Schimmel, B. Yilmaz, Comparison of trueness and margin quality of additively and subtractively manufactured definitive resin-based laminate veneers, J. Prosthet. Dent. 133 (2025) 184–192.
[11] A. Kessler, T. Reichert, S. Lindner, A. Liebermann, M. El Gezawi, D. Kaisarly, Influence of additive and subtractive zirconia and lithium disilicate manufacturing on tensile bond strength and surface topography, J. Prosthet. Dent. 132 (2024), 623.e1-623.e7.
[12] W. Wang, H. Yu, Y. Liu, X. Jiang, B. Gao, Trueness analysis of zirconia crowns fabricated with 3-dimensional printing, J. Prosthet. Dent. 121 (2019) 285–291.
[13] G. Ruggiero, R. Sorrentino, P. Venezia, G. Luongo, F. Zarone, Qualitative aspects and minimum requirements of milling machines in digital dentistry: a narrative review, Digit. Dent. J. 1 (2025) 100010.
[14] A.V. Nguyen, N.T.N. Vo, T.T. Nguyen, S.M. Tong, Evaluation of the trueness and precision of ceramic laminate veneers fabricated with four computer-aided manufacturing methods, Adv. Appl. Ceram. 123 (2024) 48–55.
[15] M.R. Baig, S.S.B. Qasim, J.K. Baskaradoss, Marginal and internal fit of porcelain laminate veneers: a systematic review and meta-analysis, J. Prosthet. Dent. 131 (2024) 13–24.
[16] Y. Lakhdar, C. Tuck, J. Binner, A. Terry, R. Goodridge, Additive manufacturing of advanced ceramic materials, Prog. Mater. Sci. 116 (2021) 100736.
[17] S.A. Mosaddad, J. Peláez, R.A. Panadero, S. Ghodsi, M. Akhlaghian, M.J. Suárez, Do 3D printed and milled tooth-supported complete monolithic zirconia crowns differ in accuracy and fit? A systematic review and meta-analysis of in vitro studies, J. Prosthet. Dent. 133 (2025) 383–393.
[18] X. Liu, A.B. Cameron, K.H. Haugli, A.A. Mougios, N.C.K. Heng, J.J.E. Choi, Accuracy of lithium disilicate and polymer-infiltrated ceramic-network (PICN) ceramic restorations fabricated from subtractive manufacturing: a systematic review of in vitro studies, J. Dent. (2025) 105872.
[19] R.O. Pilecco, C.P. Zucuni, A.B.G.d. Carvalho, G.d.S.F.A. Saavedra, R.M.d. M. Marinho, G.K.R. Pereira, L.F. Valandro, Polishing the bonding surface, before or after crystallization, does not alter the fatigue behavior of bonded CAD-CAM lithium disilicate, J. Mech. Behav. Biomed. Mater. 142 (2023) 105794.
[20] Y. Zhang, S. Vardhaman, C.S. Rodrigues, B.R. Lawn, A critical review of dental lithia-based glass-ceramics, J. Dent. Res. 102 (2023) 245–253.
[21] C.J. Roser, R. Erber, P. Rammelsberg, C.J. Lux, A. Kurt, S. Rues, F.S. Schwindling, C. Herpel, Osteoblast behaviour on zirconia fabricated by additive and subtractive technology, Ceram. Int. 49 (2023) 8793–8800.
[22] J. Schweiger, D. Edelhoff, O. Schubert, 3D printing of ultra-thin veneers made of lithium disilicate using the LCM method in a digital workflow: a feasibility study, J. Esthet. Restor. Dent. 36 (2024) 588–594.
[23] G. Su, Y. Zhang, C. Jin, Q. Zhang, J. Lu, Z. Liu, Q. Wang, X. Zhang, J. Ma, 3D printed zirconia used as dental materials: a critical review, J. Biol. Eng. 17 (2023) 78.
[24] E. Prause, J. Hey, F. Schmidt, R. Nicic, F. Beuer, A. Unkovskiy, The assessability of approximal secondary caries of non-invasive 3D-printed veneers depending on the restoration thickness-an in vitro study, Bioengineering (Basel) 10 (2023) 992.
[25] Z.N. Al-Dwairi, R.M. Alkhatatbeh, N.Z. Baba, C.J. Goodacre, A comparison of the marginal and internal fit of porcelain laminate veneers fabricated by pressing and CAD-CAM milling and cemented with 2 different resin cements, J. Prosthet. Dent. 121 (2019) 470–476.
[26] A. Alenezi, M. Alsweed, S. Alsidrani, B.R. Chrcanovic, Long-term survival and complication rates of porcelain laminate veneers in clinical studies: a systematic review, J. Clin. Med. 10 (2021) 1074.
[27] S. Karlsson, I. Landahl, G. Stegersjö, P. Milleding, A clinical evaluation of ceramic laminate veneers, Int. J. Prosthodont. 5 (1992) 447–451.
[28] H. Dumfahrt, H. Schäffer, Porcelain laminate veneers. A retrospective evaluation after 1 to 10 years of service: part II–clinical results, Int. J. Prosthodont. 13 (2000) 9–18.
[29] R. Abualsaud, H. Alalawi, Fit, precision, and trueness of 3D-printed Zirconia crowns compared to milled counterparts, Dent. J. (Basel) 10 (2022) 215.
[30] B. Camargo, E. Willems, W. Jacobs, K. Van Landuyt, M. Peumans, F. Zhang, J. Vleugels, B. Van Meerbeek, 3D printing and milling accuracy influence full-contour zirconia crown adaptation, Dent. Mater. 38 (2022) 1963–1976.
[31] H.J. Hsu, S.Y. Lee, C.P. Jiang, R. Lin, A comparison of the marginal fit and mechanical properties of a zirconia dental crown using CAM and 3DSP, Rapid Prototyp. J. 25 (2019) 1187–1197.
[32] Y.K. Kim, J.S. Han, H.I. Yoon, Evaluation of intaglio surface trueness, wear, and fracture resistance of zirconia crown under simulated mastication: a comparative analysis between subtractive and additive manufacturing, J. Adv. Prosthodont. 14 (2022) 122–132.
[33] H. Lerner, K. Nagy, N. Pranno, F. Zarone, O. Admakin, F. Mangano, Trueness and precision of 3D-printed versus milled monolithic zirconia crowns: an in vitro study, J. Dent. 113 (2021) 103792.
[34] B. Li, Q. Jiang, D. Meng, Evaluation of the trueness and adaptation of zirconia crowns fabricated with stereolithography, Dent. Mater. J. 42 (2023) 441–448.
[35] R. Li, H. Chen, Y. Wang, Y. Sun, Performance of stereolithography and milling in fabricating monolithic zirconia crowns with different finish line designs, J. Mech. Behav. Biomed. Mater. 115 (2021) 104255.
[36] R. Li, T. Xu, Y. Wang, Y. Sun, Accuracy of zirconia crowns manufactured by stereolithography with an occlusal full-supporting structure: an in vitro study, J. Prosthet. Dent. 130 (2023) 902–907.
[37] J. Lyu, X. Yang, Y. Li, J. Tan, X. Liu, Dimensional accuracy and clinical adaptation of monolithic zirconia crowns fabricated with the nanoparticle jetting technique, J. Prosthet. Dent. (2024), 985.e1-985.e7.
[38] J. Meng, Q. Lian, S. Xi, Y. Yi, Y. Lu, G. Wu, Crown fit and dimensional accuracy of zirconia fixed crowns based on the digital light processing technology, Ceram. Int. 48 (2022) 17852–17863.
[39] J.M. Moon, C.S. Jeong, H.J. Lee, J.M. Bae, E.J. Choi, S.T. Kim, Y.B. Park, S.H. Oh, A comparative study of additive and subtractive manufacturing techniques for a Zirconia dental product: an analysis of the manufacturing accuracy and the bond strength of porcelain to Zirconia, Materials (Basel) 15 (2022) 5398.
[40] A. Refaie, A. Fouda, C. Bourauel, L. Singer, Marginal gap and internal fit of 3D printed versus milled monolithic zirconia crowns, BMC Oral Health 23 (2023) 448.
[41] M. Revilla-León, M.M. Methani, D. Morton, A. Zandinejad, Internal and marginal discrepancies associated with stereolithography (SLA) additively manufactured zirconia crowns, J. Prosthet. Dent. 124 (2020) 730–737.
[42] W. Wang, J. Sun, Dimensional accuracy and clinical adaptation of ceramic crowns fabricated with the stereolithography technique, J. Prosthet. Dent. 125 (2021) 657–663.
[43] C. Marouki, A. Shamon, P. Svanborg, Evaluation of fit and accuracy of single crowns fabricated from self-glazed zirconia compared with milled zirconia, J. Prosthet. Dent. 131 (2024) 1105–1110.
[44] A.B. Cameron, J.J.E. Choi, A. Ip, N. Lyons, N. Yaparathna, A.E. Dehaghani, S. Feih, Assessment of the trueness of additively manufactured mol3% zirconia crowns at different printing orientations with an industrial and desktop 3D printer compared to subtractive manufacturing, J. Dent. 144 (2024) 104942.
[45] F.H. Alhamoudi, Comparing the accuracy of crown fitting between milling and 3D printing techniques using CAD/CAM technologies, Technol. Health Care 32 (2024) 2755–2768.
[46] A. Al-Ramadan, R. Abualsaud, Y.A. Al-Dulaijan, A.M. Al-Thobity, H. Alalawi, Accuracy and fit of ceramic filled 3D-printed resin for permanent crown fabrication: an in vitro comparative study, Prosthesis 6 (2024) 1029–1041.
[47] A. Ioannidis, J.M. Park, J. Hüsler, D. Bomze, S. Mühlemann, M. Özcan, An in vitro comparison of the marginal and internal adaptation of ultrathin occlusal veneers made of 3D-printed zirconia, milled zirconia, and heat-pressed lithium disilicate, J. Prosthet. Dent. 128 (2022) 709–715.
[48] A. Daghrery, T.S. Vinothkumar, H. Majrashi, G. Faqihi, R. Gofshi, S. Almasoudi, R. Madkhali, W.Y.H. Lam, H. Lunkad, H. Chourasia, A. Chaurasia, Dimensional accuracy of additive and subtractive manufactured ceramic-reinforced hybrid composite inlays: a CBCT-based in vitro study, Sci. Rep. 15 (2025) 6048.
[49] N.V. Anh, V.T.N. Ngoc, T.M. Son, H.V. Hai, N.T. Tra, Comparison of the marginal and internal fit of ceramic laminate veneers fabricated with four different CAM techniques, Int. J. Prosthodont. 38 (2025) 324–330.
[50] A.-E. Anghel-Lorinți, A.-B. Faur, R.N. Rotar, A. Jivănescu, Trueness and internal fit of 3D printed provisional veneers: an in vitro comparative study, Bioengineering 11 (2024) 1204.
[51] M. Noh, H. Lee, W. Lee, J. Kim, J. Kim, Evaluation of internal and marginal accuracy (trueness and precision) of laminates using DLP printing and milling methods, Biomimetics 10 (2025) 67.
[52] G. Çakmak, M.B. Donmez, D. Yılmaz, H.I. Yoon, Ç. Kahveci, S. Abou-Ayash, B. Yilmaz, Fabrication trueness and marginal quality of additively manufactured

resin-based definitive laminate veneers with different restoration thicknesses, J. Dent. 144 (2024) 104941.
[53] G. Verniani, M. Ferrari, D. Manfredini, E.Ferrari Cagidiaco, A randomized controlled clinical trial on lithium disilicate veneers manufactured by the CAD–CAM method: digital versus hybrid workflow, Prosthesis 6 (2024) 329–340.
[54] R. Sasany, S.M. Ucar, S.A. Mosaddad, V.Rodríguez Alonso, Effect of polydopamine surface treatment on the mechanical properties of zirconia and resin occlusal veneers fabricated using additive and subtractive manufacturing: an in vitro study, J. Dent. 159 (2025) 105805.
[55] A. Liebermann, A. Schultheis, F. Faber, P. Rammelsberg, S. Rues, F.S. Schwindling, Impact of post printing cleaning methods on geometry, transmission, roughness parameters, and flexural strength of 3D-printed zirconia, Dent. Mater. 39 (2023) 625–633.
[56] I.O.f. Standardization, ISO 5725-2:2019, Accuracy (Trueness and Precision) of Measurement Methods and Results. Part 2: Basic Method For the Determination of Repeatability and Reproducibility of a Standard Measurement Method, International Organization for Standardization, Geneva, Switzerland, 2019.
[57] M.B. Donmez, G. Çakmak, D. Yılmaz, M. Schimmel, S. Abou-Ayash, B. Yilmaz, A. Peutzfeldt, Bond strength of additively manufactured composite resins to dentin and titanium when bonded with dual-polymerizing resin cements, J. Prosthet. Dent. 132 (2024), 1067.e1-1067.e8.
[58] A. Bagegni, J. Borchers, S. Beisel, S.B.M. Patzelt, K. Vach, R. Kohal, Bonding strength of various luting agents between zirconium dioxide crowns and titanium bonding bases after long-term artificial chewing, Materials 16 (2023) 7314.
[59] Y.A. Lim, J.M. Kim, Y. Choi, S. Park, Evaluation of fitness and accuracy of milled and three-dimensionally printed inlays, Eur. J. Dent. 17 (2023) 1029–1036.
[60] T. Graf, K.J. Erdelt, J.F. Güth, D. Edelhoff, O. Schubert, J. Schweiger, Influence of pre-treatment and artificial aging on the retention of 3D-printed permanent composite crowns, Biomedicines 10 (2022) 2186.
[61] H. Zamzam, A. Olivares, A. Fok, Load capacity of occlusal veneers of different restorative CAD/CAM materials under lateral static loading, J. Mech. Behav. Biomed. Mater. 115 (2021) 104290.
[62] Ł. Czechowski, B. Dejak, B. Konieczny, M. Krasowski, Evaluation of fracture resistance of occlusal veneers made of different types of materials depending on their thickness, materials 16 (2023) 6006.
[63] N. Fulde, S. Wille, M. Kern, Fracture resistance and wear behavior of ultra-thin occlusal veneers made from translucent zirconia ceramics bonded to different tooth substrates, J. Esthet. Restor. Dent. 37 (2025) 1463–1473.
[64] J.F. Bates, G.D. Stafford, A. Harrison, Masticatory function - a review of the literature. III. Masticatory performance and efficiency, J. Oral Rehabil. 3 (1976) 57–67.
[65] L. Ling, T. Lai, P.-T. Chung, S. Sabet, V. Tran, R. Malyala, A novel 3D-printing model resin with low volumetric shrinkage and high accuracy, Polymers 17 (2025) 610.
[66] P. Maldonado, M.B. Dönmez, M.E. Güven, M. Schimmel, M. Revilla-León, G. Çakmak, B. Yilmaz, Digital analysis of fabrication accuracy and fit in additively and subtractively manufactured implant-supported fixed complete dentures, J. Dent. 150 (2024) 105332.
[67] J. Sun, X. Chen, J. Wade-Zhu, J. Binner, J. Bai, A comprehensive study of dense zirconia components fabricated by additive manufacturing, Addit. Manuf. 43 (2021) 101994.
[68] E. Caussin, C. Moussally, S.Le Goff, T. Fasham, M. Troizier-Cheyne, L. Tapie, E. Dursun, J.-P. Attal, P. François, Vat photopolymerization 3D printing in dentistry: a comprehensive review of actual popular technologies, Materials 17 (2024) 950.
[69] G. Çakmak, A.R. Cuellar, M.B. Donmez, S. Abou-Ayash, W.-E. Lu, M. Schimmel, B. Yilmaz, Effect of printing layer thickness on the trueness of 3-unit interim fixed partial dentures, J. Prosthet. Dent. 131 (2024) 718–725.
[70] G. Çakmak, A.R. Cuellar, M.B. Donmez, M. Schimmel, S. Abou-Ayash, W.-E. Lu, B. Yilmaz, Effect of printing layer thickness on the trueness and margin quality of 3D-printed interim dental crowns, Appl. Sci. 11 (2021) 9246.
[71] K. Trembecka-Wójciga, J. Ortyl, Enhancing 3D printed ceramic components: the function of dispersants, adhesion promoters, and surface-active agents in photopolymerization-based additive manufacturing, Adv. Colloid Interface Sci. 332 (2024) 103251.
[72] J.-Y. Park, Y.-N. Jung, K.-J. Jang, S.-K. Lee, S.-W. Choi, Y.-S. Lee, Y.P. Yang, K.-D. Yun, Effect of axis change on shrinkage rate of 3D-printed bioceramic zirconia fabricated via digital light processing, Biomimetics 10 (2025) 140.
[73] M. Hassanpour, P. Narongdej, N. Alterman, S. Moghtadernejad, E. Barjasteh, Effects of post-processing parameters on 3D-printed dental appliances: a review, Polymers 16 (2024) 2795.
[74] A.Z. Farkas, S.-V. Galatanu, R. Nagib, The influence of printing layer thickness and orientation on the mechanical properties of DLP 3D-printed dental resin, Polymers 15 (2023) 1113.
[75] T.H. Lee, J.S. Ahn, J.S. Shim, C.H. Han, S.J. Kim, Influence of cement thickness on resin-zirconia microtensile bond strength, J. Adv. Prosthodont. 3 (2011) 119–125.
[76] R.M. Melo, R.O. Souza, E. Dursun, E.B. Monteiro, L.F. Valandro, M.A. Bottino, Surface treatments of zirconia to enhance bonding durability, Oper. Dent. 40 (2015) 636–643.
[77] M. Özcan, M. Bernasconi, Adhesion to zirconia used for dental restorations: a systematic review and meta-analysis, J. Adhes. Dent. 17 (2015) 7–26.
[78] R. Comino-Garayoa, J. Peláez, C. Tobar, V. Rodríguez, M.J. Suárez, Adhesion to zirconia: a systematic review of surface pretreatments and resin cements, Materials (Basel) 14 (2021) 2751.
[79] S. Rojas-Rueda, J. Villalobos-Tinoco, C. Conner, S. Colvert, H. Nurrohman, C. A. Jurado, Bonding protocols for lithium disilicate veneers: a narrative review and case study, Biomimetics 10 (2025) 188.
[80] D.Scaminaci Russo, F. Cinelli, C. Sarti, L. Giachetti, Adhesion to zirconia: a systematic review of current conditioning methods and bonding materials, Dent. J. (Basel) 7 (2019) 74.
[81] W. Charoenporn, T. Sornsuwan, D. Sae-Lee, P. Amornvit, P. Chaijareenont, P. Rungsiyakull, Evaluating fatigue resistance in occlusal veneers: a comparative study of processing techniques and material thickness of lithium disilicate (IPS e.max Press vs. IPS e.max CAD), BMC Oral Health 24 (2024) 1542.
[82] A.I. Taha, M.E. Hafez, An in vitro study measuring marginal gaps of inlay restorations fabricated from different CAD-CAM materials after thermocycling, BMC Oral Health 23 (2023) 974.
[83] R.B. Osman, N.M. Alharbi, Influence of preparation design and build orientation on the accuracy of ceramic-filled composite veneers printed using Tilted Stereolithography technology. An in vitro study, J. Dent. 161 (2025) 105875.
[84] A. Daghrery, H. Lunkad, K. Mobarki, M. Alhazmi, H. Khubrani, T.S. Vinothkumar, E. Jabarti, Marginal discrepancy and internal fit of 3D-printed versus milled laminate veneers: an in vitro study, J. Funct. Biomater. 15 (2024).