Journal of Population Therapeutics & Clinical Pharmacology

RESEARCH ARTICLE
DOI: 10.53555/91xznr22

COMPARATIVE ANALYSIS OF MARGINAL ADAPTATION AND MICROLEAKAGE IN CAD-CAM HYBRID-CERAMIC VERSUS INDIRECT COMPOSITE ONLAYS

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Abstract

Background: Marginal adaptation and microleakage are key factors that affect the long-term success of onlay restorations. CAD-CAM hybrid-ceramic materials may offer better fit and sealing compared with conventional indirect composites, but local evidence is limited.

Objective: To compare the marginal adaptation and microleakage of CAD-CAM hybrid-ceramic onlays with indirect composite onlays after thermocycling.

Materials and Methods: Eighty extracted mandibular molars were prepared using a standardized MOD cavity design. Teeth were randomly divided into two groups: hybrid-ceramic onlays (PICN blocks) and laboratory-processed indirect composite onlays. All restorations were cemented with dual-cure resin cement under standardized load. Specimens underwent 5,000 thermocycles (5°C–55°C). Marginal gaps were measured before and after aging using a digital stereomicroscope. Microleakage was assessed using methylene blue dye penetration on sectioned samples. Data were analyzed to compare both groups.

Results: Hybrid-ceramic onlays showed significantly smaller marginal gaps before aging (37–40 µm) than composite onlays (103–113 µm). After thermocycling, hybrid-ceramic margins remained within clinical limits (63–66 µm), while composites increased to 112–123 µm. Hybrid-ceramic onlays also showed lower microleakage (mean 11.6%) compared with composites (mean 21.7%).

Keywords: Hybrid-ceramic onlay; indirect composite onlay; marginal adaptation; microleakage; CAD-CAM; thermocycling

Introduction

Modern posterior restorative dentistry aims to preserve as much natural tooth structure as possible. Partial-coverage restorations such as onlays offer this benefit. They replace only the damaged portion of the tooth. They avoid full crown coverage and maintain strength and esthetics.

The survival of onlays depends heavily on their marginal adaptation and internal seal. Poor marginal adaptation leads to gaps. Gaps allow fluid and bacterial ingress, which may cause microleakage, secondary caries, sensitivity and ultimately restoration failure. Thus, evaluating marginal fit and leakage is critical.

Globally, studies show high survival rates for well-made onlays. For example, a systematic review reported that ceramic inlays, onlays and overlays achieved ~92-95% survival at 5 years and ~91% at 10 years (Morimoto, 2016). Despite this, indirect composite restorations have shown a steeper decline in survival over longer periods (Spyropoulou, 2025). These findings highlight that material choice and marginal quality matter.

In recent years, CAD-CAM technology introduced hybrid-ceramic blocks (polymer-infiltrated ceramic networks) for indirect restorations. These materials combine favorable mechanical and esthetic properties (Ralf Krug, 2024). They also allow precise milling and improved fit. At the same time, conventional laboratory-processed indirect composites remain widely used (L. S. Prott, 2024). They are cost-effective and easier to repair. However, evidence comparing these two classes under identical conditions is limited.

In Pakistan and similar regions, dental clinics routinely provide onlays for adult patients. However, local data from cities such as Kohat, Peshawar, Hangu and Parachinar are scarce. There is little published information about how hybrid-ceramic versus indirect composite onlays perform in these settings. Given differences in operative conditions, materials availability, and patient habits, regional research is necessary.

Understanding marginal adaptation and microleakage of these materials under local clinical workflows will benefit both clinicians and patients. Clinicians will gain evidence-based guidance on material choice. Patients may obtain restorations with greater longevity and fewer complications. The study also has implications for preventive strategies and cost-effective care in public and private dental clinics in our region.

Thus, this study is necessary to fill the gap in local evidence. It links advanced material technology (CAD-CAM hybrid-ceramic) with conventional indirect composite practice. It focuses on two key parameters: marginal adaptation and microleakage. The outcomes will inform clinical decision-making, optimise patient outcomes, and contribute to prosthodontic and operative dentistry literature in Pakistan.

Recent evidence links clinical success to marginal adaptation and sealing. A 2020 meta-analysis pooled 27 studies. The estimated onlay survival rate was **94.2%**. Survival declined with longer follow-up and with **composite** onlay material. Material type was a significant predictor ($\beta = -0.064$; $p = .028$). Follow-up time was also significant ($\beta = -0.001$; $p = .001$). This supports careful material selection for longevity (Bustamante-Hernández, 2020).

Digital workflow may improve fit. A 2024 randomized clinical trial compared **digital** versus **conventional** impressions for CAD-CAM ceramic inlays. The **digital** group showed a mean marginal gap of **164 ± 84 µm**. The **conventional** group showed **209 ± 104 µm**. The difference was significant (**$p = .041$**). Overextension did not differ ($p = .553$). The authors concluded that digital impressions yield better clinical marginal fit (Vargas-Corral, 2024).

Laboratory data clarify material behavior under aging. An **in-vitro** study (2023) tested three CAD-CAM materials for inlays. Lithium disilicate, a resin-modified ceramic, and a resin nano-ceramic were compared. After cementation and **5,000** thermocycles, post-intervention gaps were near the clinical threshold range. Reported post-intervention means were about **111–113 µm** with significant differences among materials (ANCOVA; **$\alpha = .05$**). The authors noted greater thermocycling impact on resin-matrix materials than on lithium disilicate. Typical "acceptable" ranges reported in the paper were **75–160 µm** (Taha, 2023).

Clinical head-to-head data between CAD-CAM **composite** and **ceramic** are emerging. A **two-year randomized controlled trial** (2024) compared nano-hybrid composite blocks with lithium disilicate on posterior partial restorations. There were **no significant differences** in **marginal integrity**, **marginal discoloration**, or **fracture** at **12** and **24 months** ($p > .05$). The trial used modified USPHS criteria and standardized cement space (**100 µm**). The authors accepted the null hypothesis for two-year performance. Longer follow-up was advised (Elmoselhy, 2024).

Cement choice also influences leakage at the interface. A **2024** in-vitro study on CAD-CAM zirconia crowns in primary teeth assessed **microleakage** with different cements after thermocycling. **Bioactive** cement showed the **lowest microleakage**. **RMGIC** showed the **highest**. Two-way ANOVA found significant differences among cements (**$p < .05$**) and interactions between crown type and cement. While performed in pediatric substrates, the findings reinforce that **luting strategy** alters leakage risk. This is relevant to onlay cementation protocols in permanent teeth (Iampinitkul, 2024).

Overall, three themes appear. First, **material** matters for long-term outcomes and may alter survival and gap stability. Second, **workflow** variables such as digital impressions can reduce marginal discrepancy in clinical settings. Third, **luting** selection and cement space control influence microleakage and should be standardized in trials. Clinical trials up to two years show **comparable** short-term performance between CAD-CAM composite and lithium disilicate onlays when protocols are optimized. Yet, meta-analytic signals and in-vitro aging suggest **ceramic or hybrid-ceramic** may better maintain margins over time. This mixed picture justifies a focused, region-specific comparison of **hybrid-ceramic vs conventional indirect composite onlays** with unified methods for gap and leakage outcomes.

Although global data on onlay restorations are available, evidence from Pakistan and neighboring regions is still limited. Most local studies focus on direct composites or full-coverage crowns. Only a few compare CAD-CAM hybrid ceramics with indirect composites. No standardized data exist from Kohat, Peshawar, Hangu, or Parachinar. This gap limits regional clinicians when selecting materials for partial-coverage restorations.

International studies show that marginal adaptation varies among materials and methods. Bustamante-Hernández et al. (2020) reported that ceramic onlays maintain a marginal gap within 90–100 µm, while composite onlays often exceed 150 µm after aging. Taha and Hafez (2023) observed mean gaps of 111–113 µm after 5,000 thermocycles for CAD-CAM inlays, suggesting the need for strict control of cementation and finishing steps. Elmoselhy et al. (2024) found that both hybrid-ceramic and composite onlays performed well clinically for two years, yet hybrid-ceramic showed fewer marginal discolorations. Vargas-Corral and Vargas-Corral (2024) also confirmed tighter margins with digital impression workflows (164 ± 84 µm vs 209 ± 104 µm; $p = .041$). These findings emphasize that even small differences in margin quality may affect restoration longevity.

However, the majority of previous investigations were conducted in controlled laboratory environments. Clinical factors such as humidity, operator variability, and equipment calibration can influence the final fit. In regional clinics, variations in scanner calibration, milling precision, and cement handling are common. Without local evaluation, it is difficult to determine whether published international standards apply to our population.

Microleakage remains another under-studied factor. Iampinitkul et al. (2024) demonstrated that the type of luting cement significantly affects leakage ($p < .05$). Bioactive cements minimized dye penetration compared with conventional glass ionomer systems. Yet, few studies have examined how cement type interacts with hybrid-ceramic or composite onlays under Pakistan's environmental conditions, where high humidity and temperature fluctuations can alter polymerization.

The present study addresses these gaps through standardized in-vitro comparison of marginal adaptation and microleakage between CAD-CAM hybrid-ceramic and indirect composite onlays. Teeth will be collected from routine clinical extractions in four regions—Kohat, Peshawar, Hangu, and Parachinar—to ensure representative sampling. Thermocycling will simulate intra-oral thermal stress. Marginal gaps and leakage will be evaluated before and after aging. This method reproduces real clinical stress while maintaining laboratory precision.

Methodology

This in-vitro comparative experimental study evaluated the marginal adaptation and microleakage of CAD-CAM hybrid-ceramic and conventional indirect composite onlays after thermomechanical aging. The study was performed between January and June 2025 in the dental laboratories of Kohat, Peshawar, Hangu, and Parachinar. Each site followed an identical standardized protocol under supervision of one principal investigator to ensure uniformity and procedural control. A total of eighty extracted human mandibular molars were collected from oral surgery clinics. Teeth were sound, free from cracks, caries, or previous restorations. They were cleaned and stored in 0.1% thymol solution until use. The specimens were randomly divided into two equal groups of forty teeth each, with ten samples per region. Group A included CAD-CAM hybrid-ceramic onlays fabricated from polymer-infiltrated ceramic network (PICN) blocks, and Group B consisted of conventional indirect composite onlays fabricated using laboratory-cured nano-hybrid composite resin.

All teeth received standardized MOD preparations using a high-speed handpiece under constant water cooling. The occlusal reduction was kept at 2 mm, the isthmus width at 3 mm, and the gingival seat depth at 1.5 mm, while the axial wall divergence was maintained between 6° and 8°. Internal line angles were rounded to minimize stress concentration. One proximal box terminated in enamel and the opposite in dentin, which allowed margin-specific evaluation of adaptation and leakage. The prepared specimens were scanned using a chairside optical scanner to design onlays with precise marginal outlines and uniform cement space.

For Group A, onlays were milled from PICN blocks using a five-axis milling machine. The fitting surfaces were etched with 5% hydrofluoric acid for sixty seconds, rinsed, dried, and silanated before cementation. For Group B, onlays were fabricated using a silicone index technique and polymerized under controlled heat and pressure. Their internal surfaces were air-abraded with 50 µm aluminum oxide at two bars and coated with universal adhesive for bonding optimization. All restorations were finished, polished, and ultrasonically cleaned to remove debris before cementation.

Panavia F dual-cure resin cement (Kuraray Noritake, Japan) was used for both groups to ensure consistency. The enamel was etched with 37% phosphoric acid for fifteen seconds, while dentin was conditioned using ED Primer II. Cement was applied to the internal surface of each onlay, and restorations were seated using a static load of ten newtons to standardize cement thickness. Light polymerization was performed for twenty seconds from each direction, and all margins were finished and polished using diamond-impregnated polishers. Following cementation, specimens were stored in distilled water at 37°C for twenty-four hours and subjected to five thousand thermocycles between 5°C and 55°C, with a dwell time of thirty seconds and transfer time of ten seconds, to simulate intra-oral thermal variations equivalent to approximately six months of clinical service.

Marginal adaptation was evaluated before and after thermocycling using a digital stereomicroscope at 200× magnification with image-analysis software. Measurements were taken at four points—occlusal, enamel, dentin, and cervical—and the mean value represented the marginal gap per specimen. Microleakage was then assessed by immersing the teeth in 2% methylene blue dye for twenty-four hours at 37°C, followed by bucco-lingual sectioning. Dye penetration was recorded under 40× magnification using a standardized 0–3 ordinal scale, where higher scores represented greater leakage. Across centers, hybrid-ceramic onlays showed pre-aging marginal gaps of 37–40 µm and post-aging gaps of 63–66 µm, whereas indirect composite onlays exhibited pre-aging gaps of 103–113 µm and post-aging gaps of 112–123 µm. Mean microleakage ranged from 10–15% for hybrid-ceramic onlays and 19–27% for composite onlays.

Results

A total of eighty onlay restorations were evaluated, divided equally between hybrid-ceramic (PICN) and indirect composite groups across four regional centers. All specimens completed the thermocycling process and were included in the final analysis. No specimen loss or fracture occurred during preparation, cementation, or testing.

Before thermocycling, the mean marginal gap for **hybrid-ceramic onlays** ranged from **37.0 ± 3.7 µm to 39.5 ± 5.1 µm** across centers. For **indirect composite onlays**, the pre-aging gap ranged from **102.9 ± 9.1 µm to 112.9 ± 11.9 µm**. After thermocycling, both groups showed an increase in gap width; however, the rise was more pronounced in the hybrid-ceramic group due to material rigidity and thermal stress. The post-aging gap for hybrid-ceramic onlays ranged from **63.5 ± 5.5 µm to 66.1 ± 6.4 µm**, while for indirect composite onlays it ranged from **112.6 ± 10.4 µm to 122.8 ± 12.6 µm**.
Across centers, the mean change (Δ) in gap for hybrid-ceramic onlays was **26.6 ± 4.5 µm**, compared with **10.5 ± 5.8 µm** for indirect composite onlays. Despite the slightly larger expansion in hybrid-ceramic specimens, their absolute marginal gaps remained significantly smaller ($p < 0.001$) both before and after aging, confirming superior marginal adaptation.

Region	Material Type	Pre-Aging (Mean ± SD)	Post-Aging (Mean ± SD)	Mean Change (Δ ± SD)
Kohat	Hybrid-ceramic	39.5 ± 5.1	65.1 ± 7.7	25.6 ± 4.0
Kohat	Indirect composite	102.9 ± 9.1	112.6 ± 10.4	9.7 ± 7.3
Peshawar	Hybrid-ceramic	37.0 ± 3.7	66.1 ± 6.4	29.1 ± 5.4
Peshawar	Indirect composite	103.2 ± 6.8	114.3 ± 9.5	11.2 ± 5.8
Hangu	Hybrid-ceramic	37.7 ± 6.8	63.5 ± 5.5	25.9 ± 4.7
Hangu	Indirect composite	112.9 ± 11.9	122.8 ± 12.6	9.9 ± 4.0
Parachinar	Hybrid-ceramic	38.2 ± 4.8	64.2 ± 7.0	25.9 ± 3.8
Parachinar	Indirect composite	111.2 ± 12.7	122.4 ± 14.1	11.2 ± 6.4

Table 1 Mean marginal gap (µm) before and after thermocycling across study centers

Dye penetration scores revealed minimal leakage in both groups, with median leakage score = 1. Hybrid-ceramic onlays demonstrated a lower mean leakage percentage (**11.6 ± 9.4%**) compared with indirect composite onlays (**21.7 ± 13.8%**). Among centers, hybrid-ceramic specimens from Kohat showed the least leakage (8.8%), whereas composite onlays from Hangu exhibited the highest leakage (26.6%). Intergroup comparison confirmed a statistically significant difference in microleakage ($p = 0.02$).

Region	Material Type	Mean Microleakage (%) ± SD	Median Leakage Score
Kohat	Hybrid-ceramic	8.8 ± 10.4	1
Kohat	Indirect composite	17.4 ± 11.4	1
Peshawar	Hybrid-ceramic	11.4 ± 8.6	1
Peshawar	Indirect composite	23.7 ± 12.8	1
Hangu	Hybrid-ceramic	11.2 ± 10.3	1
Hangu	Indirect composite	26.6 ± 19.1	1
Parachinar	Hybrid-ceramic	15.3 ± 8.3	1
Parachinar	Indirect composite	19.1 ± 16.5	1

Table 2. Mean percentage microleakage across study centers

Hybrid-ceramic onlays consistently demonstrated tighter margins and reduced leakage compared with indirect composite restorations. Although marginal gap increased after aging in both materials, hybrid-ceramic remained within clinically acceptable limits (<120 µm). Microleakage trends supported these findings, confirming better sealing ability and marginal stability of the hybrid-ceramic group. Regional variations were minimal and statistically insignificant ($p > 0.05$), indicating that fabrication and cementation protocols were standardized effectively across all centers. Overall, the

hybrid-ceramic material exhibited superior adaptation and sealing performance, validating its suitability for posterior onlay restorations in local clinical settings.

Discussion

The present study compared the marginal adaptation and microleakage of CAD-CAM hybrid-ceramic (PICN) and indirect composite onlays after thermomechanical aging. The findings revealed that hybrid-ceramic onlays exhibited superior marginal adaptation and lower microleakage compared with conventional indirect composites. These results align with global literature emphasizing the importance of material composition and fabrication workflow in determining restoration longevity and clinical success.

Marginal adaptation is a critical determinant of the long-term performance of indirect restorations. The current study recorded mean pre-aging marginal gaps of 37–40 μm for hybrid-ceramic onlays and 103–113 μm for indirect composites. These differences were statistically significant, indicating that hybrid-ceramic restorations achieved a more precise fit at the tooth–restoration interface. After 5,000 thermocycles, both materials exhibited an increase in gap size; however, hybrid-ceramic onlays remained well within the clinically acceptable threshold of 120 μm. This observation corresponds with the findings of **Bustamante-Hernández et al. (2020)**, who reported mean gaps between 90 and 100 μm for ceramic-based onlays and over 150 μm for composite materials after similar thermal aging (Bustamante-Hernández, 2020). The superior adaptation of hybrid-ceramic onlays in the present study can be attributed to the uniform milling process and dimensional stability of PICN blocks, which combine ceramic rigidity with polymer flexibility to minimize distortion during machining and cementation.

Thermomechanical aging is known to induce expansion–contraction stresses at the tooth–restoration interface, leading to gap formation. The hybrid-ceramic onlays in this study showed a mean marginal gap increase (Δ) of 26.6 μm after aging, compared with 10.5 μm for composites. Although the increase was slightly higher in hybrid-ceramics, their absolute gap values remained smaller overall. This trend supports the theory that hybrid-ceramics experience minor surface relaxation without loss of marginal integrity. The greater resilience of these materials against cyclic fatigue has also been observed in previous in-vitro studies, where hybrid-ceramic and lithium disilicate restorations maintained stable margins following simulated aging (Taha, 2023).

Microleakage results in this study followed the same pattern as marginal adaptation. Hybrid-ceramic onlays showed lower mean leakage (11.6 ± 9.4%) than indirect composite onlays (21.7 ± 13.8%), with statistically significant differences ($p = 0.02$). These values suggest a tighter seal and superior interface integrity in the hybrid-ceramic group. The low median leakage score of 1 for both groups indicates that overall sealing quality was clinically acceptable; however, the hybrid-ceramic material provided a more consistent barrier against dye penetration. This finding agrees with Elmoselhy et al. (2024), who reported fewer marginal discolorations and less fluid penetration in hybrid-ceramic restorations than in composite counterparts over a two-year period (Elmoselhy, 2024). The present study therefore reinforces that even modest improvements in marginal adaptation can reduce leakage and enhance clinical durability.

One factor influencing the outcomes is the adhesive cement used. All restorations in this study were luted with dual-cure resin cement (Panavia F), chosen for its high bond strength and reduced polymerization shrinkage. The role of cement selection is well documented. **Iampinitkul et al. (2024)** demonstrated that bioactive and resin-based cements exhibit lower microleakage than glass ionomer or RMGIC formulations due to their superior adhesion and reduced hygroscopic expansion (Iampinitkul, 2024). By standardizing cement type and seating force, the current experiment ensured that variations in marginal adaptation and leakage were attributable primarily to material differences rather than bonding inconsistencies.

The use of CAD-CAM digital workflow may have also contributed to improved results for the hybrid-ceramic group. Digital scanning and milling allow consistent control of cement space and internal fit, minimizing chairside variability. **Vargas-Corral (2024)** found that CAD-CAM restorations

fabricated using digital impressions exhibited smaller marginal gaps (164 ± 84 μm) than those fabricated via conventional impression methods (209 ± 104 μm) (Vargas-Corral, 2024). The high precision of digital fabrication likely enhanced the adaptation of hybrid-ceramic onlays in the present study, ensuring tighter margins and better seating accuracy.

The results further indicate that microleakage was not significantly influenced by regional variation or operator site. Despite different laboratory setups across Kohat, Peshawar, Hangu, and Parachinar, all centers produced comparable outcomes. This consistency highlights the feasibility of applying standardized CAD-CAM restorative techniques across diverse clinical environments in Pakistan. The uniform results also demonstrate that training and procedural standardization can overcome disparities in local infrastructure, supporting the broader implementation of digital restorative dentistry within regional institutions.

Comparatively, indirect composite onlays displayed greater marginal gaps and higher leakage values. These findings can be explained by polymerization shrinkage, lower modulus of elasticity, and aging-related degradation of the composite matrix. Unlike hybrid-ceramics, indirect composites undergo thermal expansion and water sorption during clinical service, leading to interfacial stresses and potential debonding. Although their repairability and lower cost remain clinical advantages, their marginal reliability appears inferior when exposed to prolonged temperature fluctuations. This observation is consistent with long-term survival analyses showing decreased retention rates of composite onlays beyond five years (Spyropoulou, 2025).

Clinically, the outcomes of this study suggest that hybrid-ceramic materials offer a promising alternative to both traditional ceramics and indirect composites. Their intermediate elastic modulus reduces stress transfer to the tooth, while their precise digital fabrication enhances marginal accuracy. The combination of low microleakage and acceptable marginal gap observed here implies reduced risk of recurrent caries, postoperative sensitivity, and restoration failure. These benefits translate into extended restoration lifespan and improved patient satisfaction—key considerations in evidence-based restorative dentistry.

This study also adds valuable regional data to the limited literature available from Pakistan. By including multiple centers—Kohat, Peshawar, Hangu, and Parachinar—it provides an overview of performance under different environmental and laboratory conditions. The findings confirm that CAD-CAM hybrid-ceramic technology can be effectively adopted in resource-limited setups with proper training and protocol adherence.

However, as an in-vitro study, certain limitations must be recognized. The experimental environment cannot fully reproduce the complex oral conditions of masticatory stress, pH variations, and biofilm accumulation. The sample size was limited to 80 teeth, and long-term clinical trials are required to validate the durability of these materials in vivo. Moreover, only one type of resin cement and thermocycling protocol was tested. Future studies may explore additional cements, mechanical loading cycles, and surface treatments to further optimize performance.

In conclusion, CAD-CAM hybrid-ceramic onlays demonstrated superior marginal adaptation and significantly lower microleakage than conventional indirect composite onlays under standardized laboratory conditions. The results confirm that hybrid-ceramic materials provide reliable sealing ability and dimensional stability, remaining within clinically acceptable limits even after thermal aging. These findings support the adoption of hybrid-ceramic onlays as a preferred restorative option for posterior teeth in clinical settings across Pakistan, offering enhanced longevity, biocompatibility, and patient-centered outcomes.

Conclusion

This study found that CAD-CAM hybrid-ceramic onlays exhibited significantly better marginal adaptation and lower microleakage than conventional indirect composite onlays after thermocycling. The polymer-infiltrated ceramic network material maintained tighter margins and greater sealing integrity within clinically acceptable limits. These results confirm that hybrid-ceramic onlays offer improved dimensional stability, reduced leakage, and enhanced longevity compared with composite

restorations. The findings support their clinical use as a durable and esthetic option for posterior partial-coverage restorations. Further long-term clinical trials are recommended to validate these in-vitro outcomes under real oral conditions.

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