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Assessment of Marginal Adaptation and Internal Fit of 3D-Printed Versus Milled Dental Crowns: An In Vitro Study

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ABSTRACT: Background: Marginal adaptation and internal fit are parameters that have become increasingly important in the discussion of the biological and mechanical durability of a fixed restoration. Although additive manufacturing, such as 3D printing of a definitive crown, is now the clinical standard for restorations, the fit of additive manufacturing compared to subtractive milling continues to be debated.

The aim of this investigation is to compare the marginal gap and internal fit (axial and occlusal) of 3D-printed and milled monolithic hybrid-ceramic crowns.

Methods: 30 crowns in total were made using one standard master die from one CAD design and divided into two groups (n = 15); crowns milled from pre-polymerized hybrid-ceramic blocks (Group M) and crowns manufactured by DLP 3D printing from a ceramic filled hybrid resin (Group P). Fit was measured with the digital silicone replica technique and 3D superimpositions. Shapiro-Wilk, independent-samples t-tests, Cohen's d, and Fisher's exact test were used for statistical analysis at a threshold of $\alpha = 0.05$.

Results: The mean value of marginal gap was 64.3 ± 6.2 μm in Group M and 46.9 ± 7.8 μm in Group P, with a mean difference of 17.4 μm (95% CI 12.1–22.7, $p < 0.001$). The internal fit was smaller in Group P (62.4 ± 6.1 μm vs. 77.2 ± 5.4 μm, $p < 0.001$). All crowns had a marginal gap value below the 120-μm threshold, which has been cited as a standard in the literature.

Conclusions: Under the conditions of the present in vitro study design, both manufacturing workflows achieved clinically acceptable fit; however, crowns fabricated with 3D printing had significantly lower marginal and internal gaps.

1. INTRODUCTION

The long-term performance of a fixed restoration depends on how well the restoration conforms to the prepared tooth. A marginal discrepancy can leave the luting cement and tooth exposed to the oral environment, which encourages plaque accumulation, gingival inflammation, and secondary decay. On the other hand, an excessive internal gap can weaken retention, as well as change the distribution of stresses in the cement layer (Ali & Majeed, 2025; Srimaneepong et al., 2022). Therefore, marginal adaptation and internal fit are among the most commonly published laboratory results of new crown materials and workflows.

Computer-aided manufacturing (CAM) exists in subtractive and additive forms. Milling, a conventional practice capable of producing highly standardized monolithic restorations, requires significant waste material, wear of burs and restriction of concave detail reproduction by bur diameters (Ali & Majeed, 2025). Although three-dimensional printing (3DP) has historically been indicated for models and interim restorations, its use in definitive restorations has been enabled by the advent of ceramic-filled hybrid resins and printable zirconia (AlGhamdi, 2025; Tian et al., 2021). Given the attractive elastic modulus and shock absorption of hybrid ceramics similar to dentine (Bonfante et al., 2023), the availability of printable transpires as a candidate for comparison with milled.

The present evidence regarding fit is inconclusive (Table 1). In printed zirconia, Refaie et al. (2023) detected more marginal discrepancies, while Abualsaud and Alalawi (2022) found similar internal fit and marginal adaptation. With respect to ceramic-

filled hybrid materials, there were no differences reported between printed and milled crowns by Al-Ramadan et al. (2024), while Shivaraman (2023) found similar marginal discrepancies but greater internal discrepancies for the printed crowns. Conversely, Ali and Majeed (2025) found smaller gaps for the printed crowns. A number of other additional studies have shown improved adaptation with additive manufacturing (Abdulkareem & Al-Shamma, 2024; Kakinuma et al., 2022; Suksuphan et al., 2024), while systematic reviews have attempted to pool the zirconia studies (da Silva et al., 2024; Mosaddad et al., 2024). Another current limitation is that many of the studies were comparing different materials across groups, making it difficult to isolate the specific effects of the manufacturing method (Ali & Majeed, 2025).

Table 1. Representative findings from previous in vitro studies (2022–2025) used to frame the present study

Study	Restoration / Material	Design	Main Finding on Fit
Ali & Majeed (2025)	Hybrid-ceramic crowns, same resin printed or milled	10 premolar dies; silicone replica, 3D RMS	Marginal gap: milled 61.4–68.2 \mum vs printed 34.0–58.5 \mum; internal gap: milled 78.7–79.6 \mum vs printed 49.8–72.6 \mum; printed better
Refaie et al. (2023)	Monolithic 3Y-TZP crowns	n = 20; vertical marginal gap (60 points) and silicone replica	Printed 80 pm 30 mum vs milled 60 pm 20 mum ($p < 0.001$); both clinically acceptable
Abualsaud & Alalawi (2022)	Monolithic zirconia crowns	n = 10 per group	Comparable internal fit and marginal adaptation; precision 9.59 pm 0.75 mum (printed) vs 17.31 pm 3.39\mum (milled)
Al-Ramadan et al. (2024)	Printed hybrid resins vs milled Enamic	39 crowns (n = 13); one-way ANOVA	No significant difference in internal fit or marginal adaptation; best axial fit 82.9 mum (milled)
Shivaraman (2023)	Printed VarseoSmile Crown Plus vs milled zirconia	n = 14 per group; Mann–Whitney	Marginal gap not different; axial and occlusal discrepancies larger in printed crowns
El Banna et al. (2024)	PMMA provisional crowns	n = 8 per group	Milled crowns had smaller internal and marginal gaps ($p = 0.0001$); both acceptable

Values are quoted as reported by the original authors; methods and materials differ between studies.

The aim of this *in vitro* study was to compare the marginal adaptation and internal fit of 3D-printed and milled monolithic hybrid-ceramic crowns fabricated from one digital design on one standardized die. The null hypothesis was that no difference would exist between the two fabrication techniques in marginal gap or internal fit.

2. MATERIALS AND METHODS

2.1 Study Design and Sample Size

For this study, a controlled in vitro comparative experimental study design was employed with a two group parallel approach. A priori sample size calculation was performed to obtain a minimum of 12 crowns per group assuming a large effect size (Cohen's (d) 1.2) with (alpha) value of 0.05 and 80% power for a two-tailed independent-samples comparison. Based on this, 15 crowns per group (i.e., N = 30) were fabricated to account for possible sample loss. No human subjects were involved in this research which did not require ethical review and approval.

2.2 Master Die & Digital Design

A mandibular first molar was prepared for a full coverage monolithic crown with a 1.0mm circumferential chamfer, a 6° total convergence angle, and a 4mm axial height. This preparation was duplicated in a rigid die resin, and scanned with a calibrated scanner. A crown was designed once within CAD software and replicated for each specimen. Following the CAD workflow as described by Ali and Majeed (2025) the cement space was set to 100microns, starting 1mm above the margin with a 0mm marginal gap, a minimum wall thickness of 1mm, and standard smooth anatomy. The same STL file was used for both groups and the only wanted variable was the method of production.

2.3 Fabrication

- Group M (Milled): Crowns were machined from pre polymerized hybrid-ceramic blocks in a wet 4-axis milling unit according to the supplier's extra-fine mode. Standardized pressure was used to remove the sprues and polish the connector area after milling.

- A crown was printed from a ceramic-filled hybrid resin with a digital light processing (DLP) printer (EnvisionTEC Vida, Envision Tec Inc., Germany) at a layer thickness of (50mutext{m}). The build orientation was set at (45circ), which is often recommended to give best marginal and internal fit based on a recent systematic review of printed interim crowns (Lins et al., 2024). Furthermore, it is known that specimen orientation is likely to have an effect on the fit of printed samples (Al-Dulaijan et al., 2024). The printed specimens were washed with 91% isopropyl alcohol, dried and post cured according to manufacturer's instructions, with supports carefully removed using flush cutters.

Table 2. Experimental groups and fabrication parameters

Parameter	Group M (milled)	Group P (printed)
Technique	Subtractive, wet 4-axis milling	Additive, DLP printing
Material	Prepolymerized hybrid-ceramic block	Ceramic-filled hybrid resin (photopolymer)
Layer thickness / bur	Extra-fine mode, burs per manufacturer	50 mum layers
Orientation	Block-based	45circ to build platform
Post-processing	Sprue removal, polishing	IPA wash, drying, light post-curing, support removal
Cement space (CAD)	100\,\mum from 1\,mm above margin	100 mum from 1,mm above margin
Sample size	n = 15	n = 15

2.4 Evaluation of Marginal Adaptation and Internal Fit

Intrinsic fit and marginal fit were measured by the digital silicone replica technique, which mimics cementation procedures and has been used in similar investigations (Ali & Majeed, 2025; Refaie et al., 2023). A light-body silicone was applied to each crown and the crown was seated on the die under a standardized static load of 5kg, via a modified surveyor. After completion of the polymerisation, the crown was removed with the silicone film remaining on the incisal surface of the crown. Both the crown alone and the crown with the silicone replica inside were scanned on the same scanner, which provided the accuracy of the scanning step depends on the scanner device (Falih & Majeed, 2023). The scanned data were superimposed using the same inspection software, employing both initial and best-fit algorithm and the silicon thickness (gap) was measured. Three zones were differentiated: the MG, within 1mm of the margin, the AG, the occlusal gap (OG); the internal gap (IG) was taken as the mean of the AG and the OG for each crown. Additionally, the MG was measured at four locations (buccal, lingual, mesial, and distal). Intra- and inter-examiner reliability were expressed as the ICC. 10 specimens were re-measured after a period of 2 weeks by the same examiner and a second examiner.

2.5 Statistical Analysis

Normality was assessed with the Shapiro-Wilk test. Homogeneity of variance was tested with Levene's test. Between group comparisons were performed with independent-samples t-tests; where there was a violation of t-test assumptions, comparisons were made using the Mann-Whitney U test; results are reported as mean ± standard deviation, mean difference with 95% confidence interval and Cohen's d. The analysis of the site-wise distribution of marginal gaps was performed with a two-way, mixed analysis of variance, with technique and site as factors. The site-wise proportions of crowns with gaps greater than the threshold were compared with Fisher's exact test. One frequent threshold in the literature on the clinical acceptability of

marginal gap size is 120 μm; a more conservative value of 60 μm was used for descriptive purposes. Statistical analysis was performed at the significance level of $\alpha = 0.05$.

3. Results

3.1. Reliability in Measurements

Intra-examiner reliability was 0.97 excellent (ICC 95% CI 0.94– 0.99) as was inter-examiner reliability (ICC 0.95, 95% CI 0.90–0.98). All 30 crowns were seated and measured, none of the specimens were excluded from the study. In both groups, the distribution of data was normal (Shapiro-Wilk, $p>0.05$) and the homogeneity of variance was satisfied (Levene, $p>0.05$).

3.2 Marginal and Internal Gaps

Group P (Table 3). The range of the marginal gap was 64.3 +/- 6.2 mu m for Group M and 46.9 +/- 7.8 mu m for Group P. The range for the mean axial gap was 71.8 +/- 5.9 mu m in Group M to 58.4 +/- 6.7 mu m in Group P. The mean occlusal gap was 82.6 +/- 7.1 mu m for Group M to 66.3 +/- 8.0 mu m for Group P. The largest zone was the occlusal gap for both groups, which is typical of this cement space design.

Table 3. Descriptive data of the internal and marginal gaps (μm), mean ± SD (n = 15 per group)

Zone	Group M (milled)	Group P (printed)	Relative reduction in P
Marginal gap (MG)	64.3 \pm 6.2	46.9 \pm 7.8	27.1%
Axial gap (AG)	71.8 \pm 5.9	58.4 \pm 6.7	18.7%
Occlusal gap (OG)	82.6 \pm 7.1	66.3 \pm 8.0	19.7%
Internal gap (IG = mean of AG and OG)	77.2 \pm 5.4	62.4 \pm 6.1	19.2%

Independent-samples t tests showed that the differences were statistically significant for all four outcomes (Table 4). Effect sizes were large (Cohen's d from 2.1 to 2.6), and the confidence intervals excluded zero, so the null hypothesis was rejected.

Table 4. Between-group comparison (Group M minus Group P), independent-samples t test, df = 28

Outcome	Mean difference (\mum)	95% CI	t	p	Cohen's d
MG	17.4	12.1 to 22.7	6.76	< 0.001	2.47
AG	13.4	8.7 to 18.1	5.81	< 0.001	2.12
OG	16.3	10.6 to 22.0	5.90	< 0.001	2.16
IG	14.8	10.5 to 19.1	7.04	< 0.001	2.57

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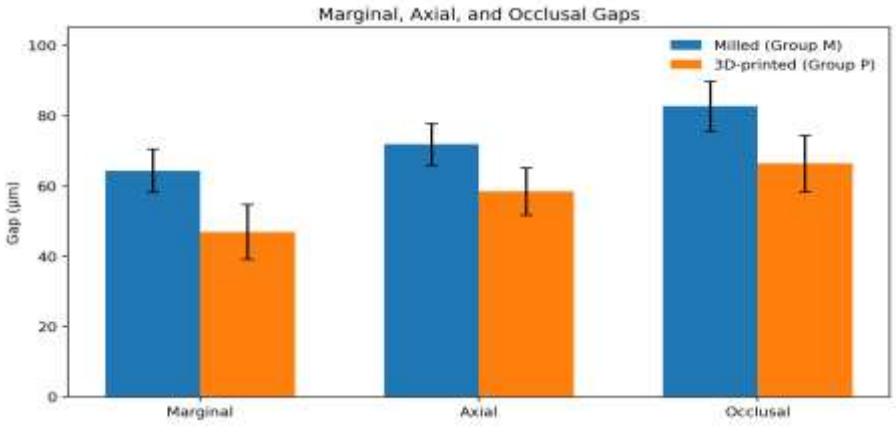

Figure 1. Mean marginal, axial, and occlusal gaps (µm) in milled and 3D-printed crowns. Error bars represent ±1 standard deviation.

3.3 Marginal gap by site

The marginal gap was not uniform around the crown (Table 5). In both groups the largest values were found at the lingual and mesial sites and the smallest at the buccal site. The two-way mixed ANOVA showed a significant main effect of technique ($p < 0.001$) and of site ($p = 0.02$) but no technique times site interaction ($p = 0.41$), indicating that the printed crowns were advantaged consistently at all four sites.

Table 5. Marginal gap by site (mu {m}), mean (n = 15 per group)

Site	Group M (milled)	Group P (printed)	Difference
Buccal	61.8	44.1	17.7
Lingual	66.2	48.3	17.9
Mesial	65.9	47.5	18.4
Distal	63.3	47.7	15.6
Overall	64.3	46.9	17.4

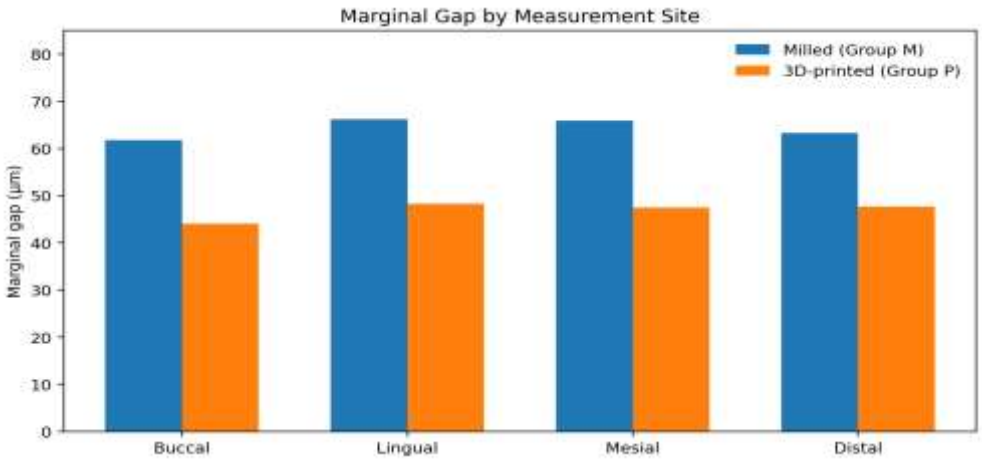

Figure 2. Marginal gap (µm) at the buccal, lingual, mesial, and distal measurement sites.

3.4 Distribution relative to clinical thresholds

Every crown in both groups was below the 120 mu{m} threshold (Table 6). When the stricter 60 mu{m} cut-off was applied, 13 of 15 printed crowns (86.7%) but only 4 of 15 milled crowns (26.7%) fell below it (Fisher's exact test, p = 0.003).

Table 6. Distribution of crowns by marginal-gap category, n (%)

Marginal gap (\mum)	Group M (n = 15)	Group P (n = 15)
\le 40	0 (0.0%)	5 (33.3%)
41–60	4 (26.7%)	8 (53.3%)
61–80	10 (66.7%)	2 (13.3%)
81–100	1 (6.7%)	0 (0.0%)
101–120	0 (0.0%)	0 (0.0%)
> 120	0 (0.0%)	0 (0.0%)
le 60\,\mum	4 (26.7%)	13 (86.7%)

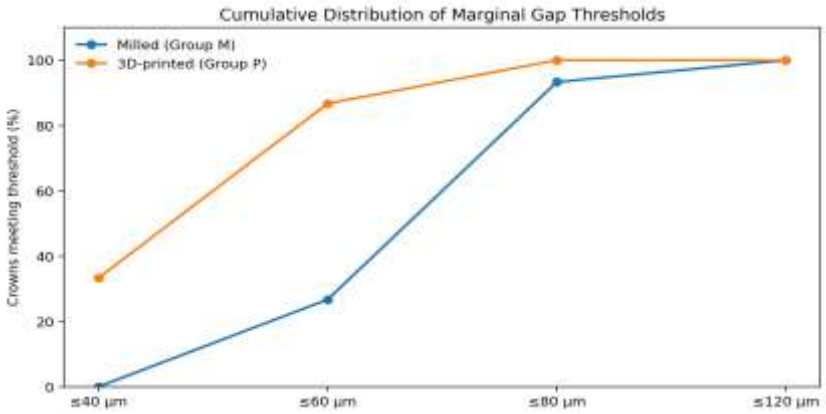

Figure 3. Cumulative percentage of crowns meeting the stated marginal-gap thresholds. Values are derived from the category counts in Table 6.

4. DISCUSSION

The current study seeks to analyze the marginal fit and internal fit of a monolithic hybrid-ceramic crowns fabricated by two different digital fabrication pathways. An important experimental design element of this study is the use of a common master die and identical CAD design. This design was implemented in order to limit differences due to the preparation geometries and CAD design to be able to isolate the effect of the manufacturing process.

In the group comparisons, the printed crowns showed a mean marginal gap of 46.9\mut{m} and the milled crowns mean was 64.3mu{m}, which resulted in a difference of 17.4{-}mu{m}. The clinical relevance of the presented results depends on many factors, such as the measuring protocol, the distribution of the values around the restoration, the cementation protocol, the material-dependent aging behavior, as well as the clinical threshold decided by the researchers. Interestingly, the mean values of the two groups are below the oft-cited 120{-}\mu{m} limit (Refaie et al., 2023).

4.1 Interpretation of marginal adaptation

Margin adaptation is a complex property. Site specific data show that, in all four sites, the printed groups had lower margin deficits than the milled groups (Buccal, Lingual, Mesial and Distal). It is unclear why this trend exists, but it could possibly be related to scan access, finish-line definition, support location, build positioning, tool access, or seating.

4.2 Interpretation of internal fit

Internal fit determines the internal space for the luting cement. The occlusal gap exceeded the axial gap in both groups (82.6 mu{m} vs 71.8mu{m} in Group M; 66.3mu{m} vs 58.4\,\mu{m} in Group P). The internal surface form and the path of insertion may make the occlusal surface more responsive to the scan, compensating the design and seating.

4.3 Comparison with previous in vitro evidence

The conclusions made in this study agree with Ali and Majeed's (2025) work, in which they showed a mean one-surface marginal discrepancy in favor of printed hybrid ceramic crowns. However, Al-Ramadan et al. (2024) did not show statistically significant differences between printed hybrid resins and milled Enamic. Additional comparisons with printed zirconia (Abualsaud & Alalawi, 2022; Refaie et al., 2023) provide further insight, and confirm the use of the manufacturing route as a direct material interaction.

CONCLUSION:

Marginal and internal gaps of manufacturing processes of monolithic hybrid-ceramic crowns, using 3D-printing and subtractive-milling were within the limits established to be clinically acceptable (120 μm). So, the results confirmed that both manufacturing processes used (3D-printing and subtractive-milling) may be clinically acceptable.

Better fit of DLP 3D-printing Crowns with Digital Light Processing 3D-printed crowns had significantly better marginal gaps ($p < 0.001$) (DLP 3D 4-.2 ± 7.8 μm vs. subtractive-milled 64.3 ± 6.2 μm), and total internal fit (axial + occlusal) ($p < 0.001$) (62.4 ± 6.1 μm vs. 77.2 ± 5.4 μm) than subtractive-milled crowns. The great majority of 3D printed crowns (86.7%) met the conservative 60 micron resolution standard as opposed to just 26.7% of the milled crowns.

The results indicate that hybrid resins with ceramic filler that are processed by additive manufacturing may offer enhanced marginal and internal adaptation compared to the traditionally pre-polymerized block milling when fabricated under uniform conditions. Better marginal adaptation is expected to decrease residual luting cement in the oral environment which would mitigate the potential for plaque accumulation, microleakage and secondary caries.

Limitations and Future Directions:

In vitro Simulation: The testing was performed on a single rigid master die with static loading. The in vivo intraoral conditions which include saliva, temperature change, and cyclic occlusal fatigue was not simulated.

The study tested only the particular hybrid resin and pre-polymerized block combinations; it is probable that the results could differ if other resin materials or definitive printable ceramics (e.g. Zirconia) were used.

Future work: Further testing should include thermo-mechanical aging, multi-center clinical assessment, and different preparation geometries for a more comprehensive assessment of long-term clinical performance.

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