

Research Article

Marginal Accuracy of CAD/CAM-Fabricated Zirconia Crowns Versus Conventional PFM Crowns: An In Vitro Study

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Abstract

Background: Marginal accuracy is an important factor influencing the clinical success and longevity of fixed dental restorations. Excessive marginal gaps may increase cement dissolution, microleakage, secondary caries, and periodontal complications. Computer-aided design and computer-aided manufacturing (CAD/CAM) zirconia crowns are increasingly used as an alternative to conventional porcelain-fused-to-metal (PFM) crowns. However, their marginal accuracy requires standardized comparative evaluation.

Objective: To compare the marginal accuracy of CAD/CAM-fabricated zirconia crowns and conventionally fabricated PFM crowns in an in vitro setting.

Materials and Methods: An in vitro comparative study was designed using 60 standardized tooth preparations, divided equally into two groups: Group A, CAD/CAM-fabricated zirconia crowns (n = 30), and Group B, conventional PFM crowns (n = 30). Marginal gaps were assessed before cementation using a calibrated

stereomicroscope at predefined points around the crown margins. Mean marginal gap measurements were compared using an independent-samples statistical test, with statistical significance set at $p < 0.05$.

Results: The values presented are hypothetical and are not actual experimental findings. The mean marginal gap was $78.4 \pm 16.2 \mu\text{m}$ for zirconia crowns and $96.7 \pm 19.5 \mu\text{m}$ for PFM crowns. The between-group difference was $18.3 \mu\text{m}$, favouring the zirconia group ($p < 0.001$). These figures must be replaced with results calculated from actual laboratory measurements before submission or publication.

Conclusion: CAD/CAM-fabricated zirconia crowns may demonstrate favourable marginal accuracy compared with conventional PFM crowns under standardized laboratory conditions. The final conclusion must be based on actual measurements and should account for fabrication protocols, measurement methods, and variability between restorations.

Keywords: Marginal accuracy, marginal gap, CAD/CAM, zirconia crowns, porcelain-fused-to-metal crowns, in vitro study.

1. Introduction

The marginal gap is commonly defined as the perpendicular distance between the internal surface of a restoration and the prepared tooth at the restoration margin. Marginal discrepancy is important because excessive gaps may contribute to cement exposure, plaque retention, marginal staining, and biological or technical complications. However, marginal fit is only one determinant of restoration performance; cementation, preparation design, occlusal loading, periodontal status, and material properties also influence clinical outcomes.

Zirconia crowns fabricated using computer-aided design and computer-aided manufacturing offer a digital workflow involving scanning, computer-based design, milling, sintering, and finishing. Their fit can be influenced by scanner accuracy, software settings, milling bur diameter, tool wear, block shrinkage compensation, sintering conditions, and finishing procedures.

Conventional PFM crowns involve impression or cast production, wax pattern fabrication, metal casting, finishing, and ceramic veneering. Each stage may introduce dimensional changes that influence final marginal adaptation.

Previous comparative research has reported smaller mean marginal gaps for CAD/CAM zirconia crowns than for conventionally fabricated metal-ceramic crowns in some settings. A 2020 comparison reported mean marginal gaps of 77.42 μm for CAD/CAM zirconia crowns and 95.86 μm for conventional metal-ceramic crowns. [1] A systematic review of zirconia restorations also found that marginal fit varied across studies and depended on manufacturing and measurement methods. [2]

Comparisons across studies are complicated by differences in tooth preparation,

impression or scanning methods, crown design, measurement locations, cementation protocols, and laboratory equipment. An in vitro comparison using standardized preparations and a consistent measurement protocol can help evaluate differences between the two fabrication approaches.

The present study compares the marginal gap of CAD/CAM-fabricated zirconia crowns and conventionally fabricated PFM crowns under standardized laboratory conditions.

2. Study Hypothesis

Null hypothesis (H_0): There is no statistically significant difference in mean marginal gap between CAD/CAM-fabricated zirconia crowns and conventionally fabricated PFM crowns.

Alternative hypothesis (H_1): There is a statistically significant difference in mean marginal gap between CAD/CAM-fabricated zirconia crowns and conventionally fabricated PFM crowns.

3. Materials and Methods

3.1 Study Design

A controlled in vitro comparative experimental study.

3.2 Study Setting

The experiment will be conducted at Sharif Medical and Dental College

3.3 Sample Size and Specimen Allocation

A proposed design includes 30 zirconia crowns and 30 PFM crowns, giving a total of 60 specimens. The final sample size should be justified using an expected between-group difference in marginal gap, the standard deviation from a comparable study or pilot experiment, a significance level of 0.05, and at least 80% statistical power.

The proposed 30 specimens per group are a planning example, not a calculated or achieved sample size. A formal sample-size calculation should be completed before fabrication begins.

Each crown should be fabricated on a standardized master preparation or a standardized set of dies with identical

preparation geometry. If multiple crowns are produced on the same die, this clustering must be considered in the analysis. Preferably, each specimen should be independently fabricated and identified.

3.4 Study Groups

Group A: CAD/CAM zirconia crowns

Crowns will be designed using a digital workflow and milled from a specified zirconia material according to the manufacturer's instructions. The zirconia type, such as 3Y-TZP or another defined formulation, must be stated because material composition and sintering behaviour may influence fit.

Group B: Conventional PFM crowns

Crowns will be fabricated using a conventional laboratory workflow involving wax pattern formation, metal casting, finishing, and ceramic veneering. The metal alloy, coping thickness, veneering ceramic, and firing protocol must be recorded.

To improve comparability, both groups should use the same master preparation geometry, margin design, cement-space target where applicable, and measurement protocol. The laboratory should document the equipment, materials, and manufacturer-recommended procedures.

3.5 Standardized Tooth Preparation

A typodont tooth or standardized master die representing a prepared posterior tooth may be used. The preparation protocol should include a predefined circumferential chamfer or shoulder finish line, standardized axial wall taper, consistent occlusal reduction, rounded internal line angles, and a clearly defined continuous finish line.

The precise reduction dimensions and taper should be selected before the experiment and applied consistently. Preparation geometry should be verified using a digital scanner or another suitable measurement method. The final manuscript should report actual dimensions.

If a single master die is used to produce multiple working dies, the method used to ensure consistency between the dies should be described.

3.6 Fabrication of Zirconia Crowns

The master preparation will be digitized using a laboratory scanner or a validated digital impression workflow. Crowns will be designed using specified CAD software, with the cement-space setting and margin-line definition recorded. The designs will be milled from the selected zirconia blocks, sintered according to the manufacturer's recommended schedule, and finished using a standardized procedure.

The following details should be recorded:

1. Scanner manufacturer and model.
2. CAD software and version.
3. Cement-space setting.
4. Milling machine and milling strategy.
5. Zirconia material and batch.
6. Sintering temperature and duration.
7. Finishing and polishing procedure.

3.7 Fabrication of PFM Crowns

Conventional PFM crowns will be fabricated using standardized preparation dies. Impressions will be made using the specified impression material and technique, and working casts will be prepared using the selected die material. Wax patterns will be produced to a standardized design, invested, cast using the specified alloy, finished, and veneered with ceramic according to the laboratory protocol.

The following details should be documented:

1. Impression material and technique.
2. Die material.
3. Wax pattern technique.
4. Investment material.
5. Metal alloy.
6. Casting method.
7. Coping thickness.
8. Ceramic veneering and firing schedule.
9. Finishing and polishing protocol.

The laboratory technician should follow the same predefined protocol for all PFM specimens to reduce variation arising from fabrication.

3.8 Assessment of Marginal Gap

The primary outcome will be the marginal gap measured in micrometres (μm). The measurement technique must be specified and applied consistently to both groups.

Direct-view stereomicroscopy before cementation may be used. Each crown will be seated on its corresponding master die using a standardized seating procedure. The marginal gap will be measured at predefined sites distributed around the crown margin, such as the buccal, lingual, mesial, and distal aspects, with additional evenly spaced sites if the measurement system permits.

A calibrated stereomicroscope or digital microscope will be used at a fixed magnification. Images will be captured and analysed using calibrated image-analysis software. Calibration should be performed using a scale of known dimensions. The examiner should be blinded to group allocation where feasible.

For each crown, the mean of all valid measurement sites will be calculated and treated as the specimen-level outcome. Individual measurement sites within the same crown must not be treated as independent specimens.

The study should define whether the measurement represents vertical marginal discrepancy, horizontal discrepancy, absolute marginal gap, or another specified measurement. These measures are related but not interchangeable.

An alternative method is the silicone replica technique, which estimates the space between the crown and die using light-body silicone stabilized with a supporting material. If this technique is selected, the seating force, seating duration, silicone material, sectioning procedure, measurement locations, and microscope settings should be standardized.

Direct-view microscopy and silicone replica measurements should not be combined without a prespecified analytical approach. [1–3]

3.9 Cementation Protocol

The primary measurement may be performed before cementation to reduce variation caused by cement viscosity, hydraulic pressure, and seating differences.

If the study aims to evaluate the marginal gap after cementation, the cement type, mixing procedure, seating load, seating duration, and excess cement removal should be standardized across both groups. Pre-cementation and post-cementation measurements should be treated as separate outcomes if both are collected. The manuscript must clearly state which measurement is the primary endpoint.

3.10 Examiner Reliability

A single trained examiner should conduct the measurements using a predefined protocol. A subset of specimens should be measured twice to assess intra-examiner reliability. If more than one examiner is involved, inter-examiner reliability should also be evaluated. Intraclass correlation coefficients may be used for continuous measurements, with confidence intervals reported. Examiner blinding and repeatability procedures should be documented.

3.11 Operational Definitions

Marginal gap: The defined distance between the crown margin and the prepared tooth or die at the specified measurement site, expressed in μm .

Mean marginal gap per crown: The arithmetic mean of the valid marginal-gap measurements recorded for a single specimen.

Clinically acceptable marginal gap: A threshold specified in advance based on the literature. A value of 120 μm is frequently used as a conventional reference point, but it should not be treated as an absolute universal boundary for clinical success. [1,2]

Specimen: One independently fabricated crown. The crown, rather than each microscopic measurement site, will be the primary unit of statistical analysis.

3.12 Statistical Analysis

Data will be analysed using SPSS, R, or another validated statistical package. The software and version should be specified in the final manuscript.

The primary outcome will be the mean marginal gap per crown. Continuous data will be summarized as mean and standard deviation when approximately normally distributed, or median and interquartile range when distributions are skewed.

The distribution of marginal-gap values will be examined using graphical methods and an appropriate normality assessment. If assumptions are satisfied, the independent-samples t-test will be used to compare mean marginal gaps between the two independent groups. Welch's t-test will be preferred if variances differ substantially. If the data are markedly non-normal and cannot be

adequately transformed, an appropriate nonparametric test, such as the Mann–Whitney U test, may be used.

The mean difference between groups will be reported with a 95% confidence interval. A two-sided p-value <0.05 will be considered statistically significant. Interpretation will emphasize the magnitude and precision of the difference rather than the p-value alone.

The proportion of crowns exceeding the prespecified marginal-gap threshold may be compared using the chi-square test or Fisher's exact test, as appropriate. If measurements are collected from multiple sites per crown, a repeated-measures or mixed-effects model may be considered for site-specific analyses, accounting for the clustering of measurements within specimens.

4. Results

Note: The following results are hypothetical examples only. They are not experimental observations and must be replaced with actual laboratory measurements before submission

Table 1. Marginal Gap of CAD/CAM Zirconia and Conventional PFM Crowns

Group	Number of crowns	Mean marginal gap (µm)	Standard deviation (µm)
CAD/CAM zirconia	30	78.4	16.2
Conventional PFM	30	96.7	19.5

Note: values only.

Table 2. Comparison of Marginal Gap Between the Two Groups

Outcome	estimate
Mean difference (zirconia – PFM)	–18.3 µm
95% confidence interval	–27.4 to –9.2 µm
p-value	<0.001

Note: statistical results only. The actual confidence interval and p-value must be recalculated from the study data.

Table 3. Distribution According to the 120-μm Reference Threshold

Marginal-gap category	CAD/CAM zirconia, n (%)	Conventional PFM, n (%)
≤120 μm	28 (93.3)	26 (86.7)
>120 μm	2 (6.7)	4 (13.3)
Total	30 (100.0)	30 (100.0)

Note: values only. The 120-μm threshold is a conventional reference, not a definitive guarantee of clinical success.

Results Narrative

The final Results section should state the number of crowns fabricated and successfully measured in each group, the mean marginal gap and standard deviation, and the between-group mean difference with a 95% confidence interval. Any specimens excluded because of fabrication defects or measurement problems should be reported, with reasons for exclusion.

If the final data demonstrate a smaller mean marginal gap in the zirconia group, the results may be described as favouring zirconia in terms of marginal adaptation under the tested laboratory conditions. If the difference is not statistically significant, the report should describe the estimate and confidence interval without claiming that the two methods are equivalent.

5. Discussion

5.1 Principal Findings

The objective of this in vitro study is to compare the marginal fit of CAD/CAM-fabricated zirconia crowns and conventionally fabricated PFM crowns under standardized laboratory conditions. The primary interpretation will depend on the observed mean marginal gap, the magnitude of the between-group difference, and the precision of the estimate.

If the actual measurements demonstrate a smaller marginal gap for zirconia crowns, the findings would suggest that the selected

digital manufacturing workflow produced better marginal adaptation than the selected conventional PFM workflow under the experimental conditions. Such a result would not establish that all CAD/CAM zirconia systems are superior to all conventional PFM systems because performance depends on the materials, equipment, design settings, and laboratory procedures used.

5.2 Comparison with Previous Research

Paul and colleagues compared CAD/CAM-fabricated monolithic zirconia crowns with conventionally fabricated metal-ceramic crowns and reported mean marginal gaps of 77.42 μm and 95.86 μm, respectively. Their study found a statistically significant difference between the groups. [1] These findings provide a useful comparison for the present research question, although the clinical setting and measurement procedures may differ from an in vitro laboratory experiment.

Svanborg's systematic review reported variation in zirconia restoration fit across the included studies and highlighted the influence of manufacturing parameters and measurement approaches. [2] The review illustrates why a single mean value should not be interpreted without considering study design, restoration type, and measurement methodology.

Differences between the current study and earlier reports may arise from the zirconia

formulation, CAD/CAM system, cement-space settings, sintering conditions, conventional casting technique, coping design, finish-line geometry, and the method used to assess the marginal gap. Comparisons should therefore be based on the actual methods and outcomes of each study rather than on the fabrication label alone.

5.3 Potential Explanations for Differences in Marginal Fit

CAD/CAM fabrication can improve standardization by allowing digital design, predefined spacer settings, and automated milling. However, the final fit remains dependent on scanner accuracy, margin detection, milling-tool geometry, tool wear, milling strategy, and sintering shrinkage compensation.

Conventional PFM fabrication involves multiple laboratory steps, including impression making, cast production, wax pattern formation, casting, finishing, and ceramic firing. Dimensional changes at different stages may influence final marginal adaptation. Nevertheless, skilled laboratory techniques can produce accurately fitting PFM crowns, and the conventional method should not be assumed to yield inferior results in every setting.

The comparison is best understood as an assessment of two complete fabrication workflows rather than a test of zirconia material alone. If the objective is to isolate the effect of material composition, the study would need a design that controls the fabrication method and other process-related differences as far as technically possible.

5.4 Clinical Significance of Marginal Gap

A smaller marginal gap may reduce the exposed cement line and contribute to favourable long-term restoration performance. However, marginal gap is a surrogate laboratory outcome rather than a direct measurement of restoration survival, recurrent caries, periodontal health, or patient satisfaction.

A frequently cited reference threshold for acceptable marginal discrepancy is approximately 120 μm , although this value is not a universal clinical boundary. [1,2] Results should report the actual distribution of gap measurements, not merely whether the group mean lies below the threshold. A mean below 120 μm does not guarantee that every crown has an acceptable margin.

Clinical outcomes also depend on cement selection, seating, oral hygiene, occlusal forces, margin location, caries risk, periodontal health, and restorative material durability. Consequently, findings from an in vitro study should not be directly translated into claims of superior clinical longevity.

5.5 Strengths

Potential strengths include standardized preparation geometry, a predefined fabrication protocol, direct comparison of two commonly used crown systems, calibrated microscopic measurement, and specimen-level statistical analysis. Blinded measurement and reliability testing may further improve methodological quality.

These strengths should be included in the final manuscript only if the procedures were actually implemented.

5.6 Limitations

As an in vitro study, the experiment cannot reproduce all intraoral conditions, including saliva, temperature changes, masticatory loading, periodontal responses, and long-term cement degradation. Results may also depend on the specific zirconia system, metal alloy, ceramic material, milling equipment, casting protocol, and laboratory technicians involved.

If one technician fabricates all crowns in a group, the results may partly reflect technician-specific performance. Likewise, using a single master die may improve standardization but limit generalizability to the diversity of clinical tooth preparations.

Microscopic measurement can be affected by site selection, calibration, magnification,

examiner judgement, and the definition of marginal discrepancy. Measuring multiple sites per crown improves characterization of the margin but does not increase the independent sample size to the number of measurement sites. These factors should be addressed in the experimental design and reported transparently.

5.7 Recommendations for Future Research

Future studies may compare additional zirconia formulations, digital scanners, milling systems, and cementation protocols. Evaluation of internal fit, marginal discrepancy after cementation, fracture resistance, and cyclic loading may provide a broader understanding of restoration performance.

Clinical studies would be required to determine whether any laboratory difference in marginal fit translates into differences in restoration survival, periodontal outcomes, or patient-reported outcomes.

6. Conclusion

This in vitro study is designed to compare the marginal gap of CAD/CAM-fabricated zirconia crowns and conventionally fabricated PFM crowns under standardized laboratory conditions. The final conclusion should be based on the measured difference, its confidence interval, and the reproducibility of the experimental protocol. If zirconia crowns demonstrate a smaller marginal gap, this would support better marginal adaptation for the particular digital workflow tested, but it would not establish universal superiority or prove improved long-term clinical outcomes.

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