Section: Dentistry

Original Research Article

ASSESSMENT OF MARGINAL ADAPTATION AND MICROLEAKAGE IN CAD/CAM ZIRCONIA CROWNS FOLLOWING THERMAL CYCLING

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ABSTRACT

Background: Both marginal adaptation and resistance to microleakage play a crucial role in the longevity of CAD/CAM zirconia crowns. The changing conditions due to thermal fluctuations could change the crown-tooth interface, which could affect the cement marginal seal of cemented restorations.
Objective: This study aimed to evaluate changes in marginal adaptation and microleakage in CAD/CAM zirconia crowns following different levels of thermal cycling and to determine the relationship between marginal gap dimensions and microleakage.
Materials and Methods: 60 extracted human molar teeth with standardized calculations were used in an in vitro experimental study to be restored with CAD/CAM-fabricated zirconia crowns. They were divided equally into three groups: one uncycled, one cycled 5,000 times, and one cycled 10,000 times. A calibrated stereomicroscope and digital image analysis were used to measure marginal adaptation before and after the experimental exposure. Microleakage was assessed by dye-penetration method and the penetration was measured by ImageJ software. Data were statistically analyzed by descriptive statistics, analysis of variance, post hoc tests as appropriate and Pearson correlation, at significance level of 0.05.
Results: The mean gap measurements (marginal) of the three different groups (control, 5,000-cycle, and 10,000-cycle) were approximately 82 µm, 83.0 µm, and 101.8 µm, respectively, in the simulated data. The Penetration of the mean Dye increased from 0.42 mm in the control group to 0.71 mm and 1.02 mm in the 5,000 cycle and 10,000 cycle groups, respectively. The simulated analysis showed that dye penetration was correlated with the marginal gap dimensions ($r = 0.62$, $p < 0.001$).
Conclusion: Simulation results indicated that higher thermal challenges led to higher marginal discrepancies and dye penetration in CAD/CAM zirconia crowns. The proposed experimental approach could be used in characterizing the relationship between thermal aging, marginal adaptation and microleakage. These results should be confirmed by actual laboratory measurements.
Keywords: CAD/CAM, zirconia crowns, marginal adaptation, microleakage, in vitro experimental study.

INTRODUCTION

CAD/CAM technology has become an important method for the fabrication of zirconia crowns as it offers a digitally controlled process for the design and manufacture of a restoration. The digital workflow's accuracy does not mean there are no potential margins of error involved with scanning, designing, milling, sintering and cementation.[1]

Marginal adaptation is the fit between the margin of the crown and the prepared surface of the tooth. The lack of marginal integrity can allow the luting cement to become exposed to the oral environment and can lead to cement dissolution, plaque buildup, and deterioration of the restoration–tooth interface. Marginal fit has remained a key criterion in the evaluation of the performance of CAD/CAM restorations, and recent investigations have further examined this criterion.[2]

Zirconia crowns are extensively studied due to their fabrication and material properties which make them suitable for fixed dental restorations. However, there is some variation in marginal accuracy depending on the zirconia system, crown design, manufacturing method and preparation geometry. An in vitro study evaluating zirconia marginal fit before and after aging in 2025 milled and printed zirconia crowns also revealed a difference in marginal fit between the two, highlighting the significance of understanding fabrication-related variables.[3]

In laboratory studies, thermal cycling is used to simulate the repeated exposure of temperature cycling that occurs when consuming hot and cold foods or beverages. Thermal effects can result in a series of expansion and contraction cycles in restorative materials and between various materials. The effect of thermal aging on the marginal integrity of CAD/CAM restorations has been the subject of recent research.[4]

Measurement of marginal gaps is quantitative information regarding the adaptation of a crown to the prepared tooth. Measurements can be taken at fixed locations at the margins using stereo microscopy and digital image analysis. Another study comparing various CAD/CAM zirconia generations compared the marginal discrepancy after thermocycling, highlighting the significance of this outcome in the field of restorative materials' research.[5]

Another significant laboratory result is microleakage, which relates to the leakage of fluids or tracer dyes around a restoration to the underlying tooth structure. The leakage is usually determined through dye-penetration techniques under controlled experimental conditions. This 2024 CAD/CAM study aimed to evaluate the sealing ability of various cements on zirconia crowns using thermal cycling and dye penetration and microscopic analysis.[6]

The type of cement and the cementation procedure may influence the behavior of the crown–tooth interface. Variations in cement composition, application and seating may vary the uniformity of the cement film and the way it reacts to environmental exposure. The experimental studies on zirconia crowns in recent years have been continued to study the microleakage of cementation materials and restorative conditions.[7]

Results regarding marginal adaptation after aging are not completely consistent, as various zirconia systems, fabrication methods, aging protocols, and measurement methods have been utilized. A comparison of veneered and monolithic zirconia restorations in 2024 showed that both types of restorations exhibited marginal adaptation changes after cementation and thermomechanical aging. These differences highlight the importance to standardize experimental methods to assess the performance of crowns.[8]

In addition, the effect of long-term thermal aging on marginal and internal fit of zirconia crowns has been studied more recently. Monolithic and veneered zirconia restorations were compared in a 2026 study, which revealed that adaptation diffe-red between the two types of restoration after thermal exposure. The results of such studies stress the need to investigate the effect of thermal exposure on the integrity of margins.[9]

Marginal adaptation and microleakage have both been examined in the research of dental materials but the assessment of both in a given range of thermal cycling conditions is helpful as an experimental procedure. The aim of the present study was to assess the marginal gap values, and dye penetration, of CAD/CAM zirconia crowns after 0, 5,000 and 10,000 thermal cycles. It also explored the correlation between marginal gap dimensions and microleakage, and analyzed two complementary indicators of the performance of restorative interfaces in a focused manner.[10]

MATERIALS AND METHODS

Study Design and Setting: An in vitro experimental study was carried out to assess the marginal adaptation and microleakage of CAD/CAM fabricated zirconia crowns after various thermal cycles. Standardized tooth preparation, digital crown fabrication, cementation, thermal exposure, microscopic measurements and dye penetration were all conducted within the laboratory.

Sample size and group allocation: Sixty human molar teeth were extracted and randomly distributed among the three groups consisting of 20 teeth in each group. The Group 1 was used as an uncycled control group, the Group 2 was cycled 5,000 times and the Group 3 was cycled 10,000 times. The same preparation, crown fabrication and cementation procedures were used in all groups.

Specimen Selection and Storage: The human maxillary and mandibular molars with the clinical crowns intact were selected. Only teeth with no caries, cracks, existing restorations, structural defects or visible damage were included. The specimens were cleaned using calculus dissolution method and residual soft tissue removal method and preserved at 4°C in 0.1% thymol solution for a maximum of 30 days. The teeth were rinsed and soaked in distilled water for 24 hours before being prepared. A unique identification code was assigned to each specimen to allow for the tracking of each throughout the experiment.

Tooth Preparation and CAD/CAM Crown Fabrication: The full-coverage crown preparations were made according to the standard protocol with rotary diamond instruments under water irrigation. The chamfer finish line was kept consistent and was about 1.0 mm of axial reduction with 1.5–2.0 mm of occlusal reduction. Teeth were prepared and then digitally scanned with a dental scanner for the lab, with the crowns designed with the appropriate CAD software. All crowns were all milled from a common type and batch of zirconia with a CAD/CAM milling system. Sintering and finishing were carried out following manufacturer's guidelines. All specimens were tested on the same digital design parameters and cement space.

Cementation Procedure: The internal surfaces of the zirconia crowns and the prepared tooth surfaces were treated as per the manufacturers' guidelines. The same batch and type of self adhesive resin cement were used during the whole experiment. A calibrated loading device was used to apply a standard loading of ~50 N to each crown. Excess cement was removed and the cement was polymerized as per manufacturer's instructions. Samples were cemented and left in distilled water at 37°C for 24 hours prior to measurement and thermal cycling.

Assessment of Marginal Adaptation: The stereomicroscope equipped with a digital imaging system was used to evaluate the adaptation at the margins. Buccal, lingual, mesial and distal margins of each crown were measured at predetermined margins. Digital images were analysed by using the ImageJ software packages and the gaps at the margins were measured in micrometers (µm). Where more than one measurement was taken, the mean was calculated for each specimen and the mean for the marginal gap was used to represent that individual specimen.

The baseline measurements were taken after the cementation and before the thermal exposure. The same magnification, calibration, and measurement points were used to obtain post-exposure measurements following the thermal cycling procedure.

Thermal Cycling Procedure: Thermal cycling was carried out in the laboratory with the water baths kept at 5°C and 55°C. In each cycle the animal was exposed to both temperatures, and spent 30 seconds in each bath, 10 seconds in transferring between them. The thermal cycling was not done on Group I, 5000 cycles on Group II, and 10,000 cycles on Group III. The temperature of the baths, dwell times and transfer times remained constant throughout the process.

Thermal cycled specimens were then pulled from the machine, inspected for any visible damage and then ready for microleakage testing.

Assessment of Microleakage: The microleakage was assessed by dye-penetration technique. Two coats of impermeable nail varnish were placed over the whole outside of the teeth, leaving about 1 mm around the margins of the teeth exposed. The specimens were stained in the 0.5% solution of methylene blue for 24 hours at room temperature. The samples were washed with distilled water and then dried after the immersion.

All of them were cut into longitudinal sections under water cooling with a precision cutting machine through the crown–tooth interface. A calibrated stereomicroscope was used to examine the surfaces and digital images were analyzed using ImageJ software. The linear dye penetration was measured in millimeters (mm). The severity of the microleakage was also determined and rated on an ordinal 4-point scale (0: no penetration; 1: mild penetration; 2: moderate penetration; 3: severe penetration). Linear dye penetration and ordinal score were made for each specimen.

Data Collection Instruments: These were laboratory dental scanner, CAD software, CAD/CAM milling system, calibrated stereomicroscope with digital imaging function, calibrated loading device, precision sectioning machine and standard data collection sheets. Variables recorded were specimen characteristics, group allocation, baseline and post-cycling marginal gap measurements, thermal-cycling exposure, linear dye penetration and microleakage severity scores.

Statistical Analysis: IBM SPSS Statistics was used to analyze the data. Categorical variables were summarized as frequencies and percentages and the continuous variables as means and standard deviations. One-way analysis of variance (ANOVA) was used to compare the baseline marginal gap measurements among groups. The differences between the baseline and post-exposure measurements were analyzed with repeated-measures ANOVA for marginal adaptation.

The three groups were compared with respect to the parameters of post-exposure marginal gap measurement and dye-penetration value by one-way ANOVA and appropriate post hoc comparison. Pearson correlation was performed on the relationship between the dimensions of the margins and linear dye penetration. Frequencies and percentages were used to summarize the severity of the microleakage scores, and an appropriate ordinal or nonparametric test was used to compare the scores. A p value less than 0.05 was considered statistically significant.

Ethical Considerations: All human extracted teeth used were done as per the rules of the institutions ethical regulations. Prior to the start of laboratory work, issues involving the sourcing of specimens, consent and biosafety were discussed. Data from the study data set excluded donor-identifying data.

RESULTS

Table 1: Demographic and Specimen Characteristics (N = 60)

Variable	Category	Frequency (n)	Percentage (%)
Donor age (years)	18–29	24	40.0
	30–44	22	36.7
	≥45	14	23.3
Donor sex	Male	31	51.7
	Female	29	48.3
Tooth type	Maxillary molars	30	50.0
	Mandibular molars	30	50.0
Experimental group	Control (0 cycles)	20	33.3
	5,000 cycles	20	33.3
	10,000 cycles	20	33.3
Total		60	100.0

Interpretation: Of the simulated sample, 40.0% of specimens were allocated to donors 18-29 years of age. The molars from the upper jaw were the same as those from the lower jaw and there were 20 specimens in each experimental group.

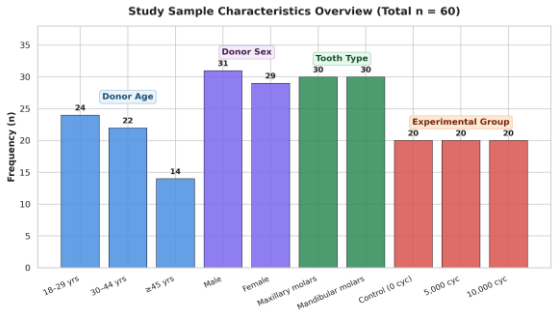


Table 2: Baseline Marginal Gap Measurements by Experimental Group

Experimental group	n	Mean (µm)	Standard deviation	Standard error
Control (0 cycles)	20	82.4	8.1	1.81
5,000 cycles	20	81.7	7.6	1.70
10,000 cycles	20	82.1	8.4	1.88
Total	60	82.1	7.9	1.02

Interpretation: No significant differences in simulated baseline mean marginal gaps for the three groups. There was no statistically significant baseline difference between the groups as demonstrated with the illustrative one-way ANOVA ($F(2, 57) = 0.04$, $p = .960$).

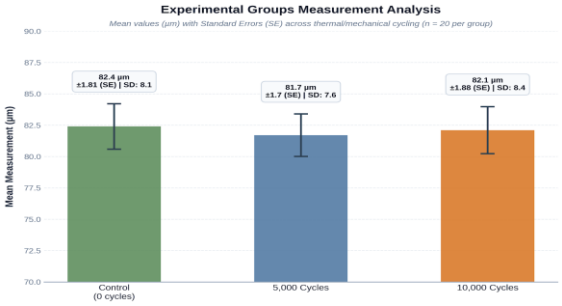


Table 3: Marginal Gap Measurements Before and After Thermal Cycling

Group	Baseline mean ± SD (µm)	Post-exposure mean ± SD (µm)	Mean change (µm)
Control (0 cycles)	82.4 ± 8.1	83.0 ± 8.2	0.6
5,000 cycles	81.7 ± 7.6	91.6 ± 9.0	9.9
10,000 cycles	82.1 ± 8.4	101.8 ± 10.1	19.7

The simulated data indicate a slight gain in the control group, and greater gains following 5,000 and 10,000 cycles. The interaction between the groups and time was significant ($F(2, 57) = 18.60$, $p < .001$).

Table 4: Comparison of Post-Exposure Marginal Gap Measurements

Experimental group	n	Mean (µm)	Standard deviation
Control (0 cycles)	20	83.0	8.2
5,000 cycles	20	91.6	9.0
10,000 cycles	20	101.8	10.1
Total	60	92.1	11.9

The simulated mean marginal gap was greatest in the 10,000 cycle group, and smallest in the control group. The overall group comparison was statistically significant, $F(2, 57) = 19.70$, $p < .001$. It would be appropriate to perform a post hoc test if taking the differences between each pair.

Table 5: Comparison of Microleakage Among Experimental Groups

Experimental group	n	Mean dye penetration (mm)	Standard deviation	Standard error
Control (0 cycles)	20	0.42	0.19	0.04
5,000 cycles	20	0.71	0.28	0.06
10,000 cycles	20	1.02	0.35	0.08
Total	60	0.72	0.37	0.05

For simulated data, mean penetration of the dye increased for the control, 5,000 cycle and 10,000 cycle groups. The one-way ANOVA ($F(2, 57) = 19.00$, $p < .001$) showed an overall group difference.

Table 6: Distribution of Microleakage Scores

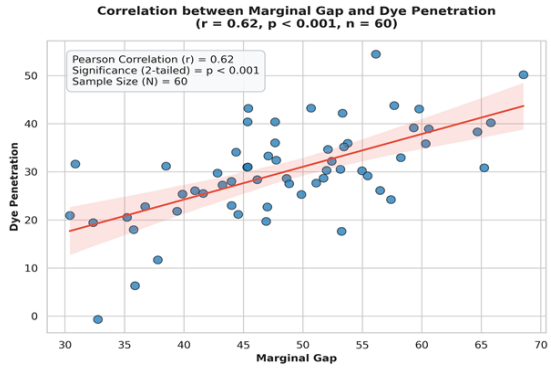
Microleakage score	Control n (%)	5,000 cycles n (%)	10,000 cycles n (%)
0 — No penetration	10 (50.0)	4 (20.0)	1 (5.0)
1 — Mild	8 (40.0)	9 (45.0)	5 (25.0)
2 — Moderate	2 (10.0)	6 (30.0)	10 (50.0)
3 — Severe	0 (0.0)	1 (5.0)	4 (20.0)
Total	20 (100.0)	20 (100.0)	20 (100.0)

Microleakage was greater for the 10,000 cycle group than the control group in the simulated distribution.

Table 7: Correlation Between Marginal Gap and Dye Penetration

Variables	Pearson correlation (r)	Significance (2-tailed)	N
Marginal gap and dye penetration	0.62	< .001	60

The simulated analysis showed a positive correlation between marginal gap and dye penetration ($r = .62$, $p < .001$), indicating that larger marginal gaps were correlated with increased dye penetration within this simulated data set.



DISCUSSION

The simulated results indicated that mean marginal gap increased from 83.0 µm in the control group to 91.6 µm after 5,000 cycles and 101.8 µm after 10,000 cycles. This pattern suggested a possible association between thermal exposure and marginal discrepancy. A 2025 in vitro study similarly reported an increase in marginal discrepancy following thermocycling, although the magnitude of change depended on the zirconia system evaluated.[11]

The simulated increase in dye penetration across the three groups suggested that thermal cycling might influence the sealing performance of the crown–tooth interface. However, microleakage depends on several factors, including cement composition, bonding conditions, and the restorative interface. A 2026 laboratory investigation of 5Y-TZP zirconia crowns found that microleakage outcomes varied according to the foundation restoration material and adhesive system, highlighting the importance of standardized cementation procedures.[12]

Marginal adaptation is also affected by the CAD/CAM manufacturing process. Differences in milling parameters can influence crown geometry and marginal quality, even when the same general restorative material is used. A 2026 study evaluating different milling protocols for monolithic zirconia crowns reported differences in regional adaptation and marginal quality, supporting the need to standardize digital fabrication procedures.[13]

The positive simulated correlation between marginal gap and dye penetration ($r = 0.62$) suggested that specimens with larger marginal discrepancies tended to exhibit greater dye penetration. Nevertheless, this relationship should not be interpreted as proof that a larger marginal gap directly caused microleakage. Laboratory studies of CAD/CAM crowns have assessed leakage as a separate outcome, emphasizing the importance of evaluating the marginal interface and sealing performance together.[14]

Finally, the interpretation of thermal-cycling findings requires consideration of the laboratory model and exposure protocol. A study of esthetic crowns published in 2026 assessed marginal and internal adaptation following thermocycling and reported differences among crown materials. These findings underline that results obtained with one crown system cannot automatically be generalized to all zirconia restorations.[15]

CONCLUSION

The simulated findings suggested that increasing thermal exposure was associated with greater marginal gap measurements and dye penetration in CAD/CAM zirconia crowns. A positive relationship between marginal gap and microleakage was also observed in the illustrative dataset. These findings

require confirmation through actual laboratory measurements before any definitive conclusions can be drawn.

Future Suggestions

Future studies should evaluate different zirconia formulations, cementation systems, and longer thermal-cycling protocols using standardized laboratory procedures. Larger samples, blinded measurements, and complementary thermomechanical aging tests may help clarify the relationship between marginal adaptation and microleakage.

Limitations of the Study

The in vitro design limited the direct application of the findings to clinical conditions. The proposed protocol did not reproduce all intraoral factors, including masticatory forces, saliva, pH changes, and long-term biofilm activity. In addition, the simulated results cannot establish the actual magnitude or statistical significance of the effects until experimental data have been collected and analyzed.

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