ORIGINAL ARTICLE

Comparative Evaluation of Marginal Adaptation, Internal Fit and Fracture Resistance of CAD/CAM Monolithic Zirconia Crowns Fabricated Using Conventional and High-Speed Sintering: An In Vitro Study

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ABSTRACT

Background

Monolithic zirconia crowns have become a routine prosthodontic option because of their strength, biocompatibility and compatibility with digital workflows. However, accelerated chairside sintering protocols may alter shrinkage, marginal adaptation, internal fit and fracture resistance.

Objective

This in vitro study compared the marginal adaptation, internal fit and fracture resistance of CAD/CAM monolithic zirconia crowns fabricated using conventional and high-speed sintering protocols.

Methods

Forty-five standardized mandibular first molar dies were prepared and digitally scanned. Full-contour crowns were designed with a 50 µm cement spacer and allocated into three groups (n=15 each): conventionally sintered 4Y-TZP zirconia (CS-Zr), high-speed sintered 4Y-TZP zirconia (HS-Zr) and CAD/CAM lithium disilicate crowns (LD) as a ceramic comparator. Marginal and internal gaps were measured using a silicone replica technique and stereomicroscopy. After adhesive cementation, thermocycling and mechanical aging, fracture resistance was tested using a universal testing machine.

Results

Mean marginal gap was significantly lower in HS-Zr (67.9 ± 8.7 µm) than CS-Zr (82.6 ± 10.9 µm) and LD (76.4 ± 9.8 µm) ($p<0.001$). Mean internal gap was lowest in HS-Zr (91.8 ± 11.6 µm), followed by CS-Zr (103.5 ± 13.4 µm) and LD (112.7 ± 15.1 µm) ($p=0.002$). Fracture resistance was significantly higher for CS-Zr (2386.4 ± 286.7 N) and HS-Zr (2264.8 ± 254.3 N) than LD (1542.3 ± 214.6 N) ($p<0.001$). Conclusion: High-speed sintered zirconia produced clinically acceptable adaptation and fracture resistance, supporting its use in single-visit posterior prosthodontics when validated material-specific protocols are followed.

Keywords

CAD/CAM; zirconia; marginal adaptation; internal fit; fracture resistance; prosthodontics; high-speed sintering

INTRODUCTION

The development of computer-aided design and computer-aided manufacturing (CAD/CAM) has transformed fixed prosthodontics by improving reproducibility, reducing laboratory variables and allowing fabrication of ceramic restorations with predictable geometry. Early CAD/CAM systems were limited by scanner resolution, software design tools and milling accuracy; however, successive advances in intraoral scanning, ceramic blocks, milling units and sintering furnaces have made monolithic ceramic crowns a common restorative option for posterior teeth [1]. In prosthodontic practice, success is no longer judged only by esthetics or strength, but by the combined behavior of fit, cement space, material stability, biological compatibility and resistance to functional fatigue [2].

Marginal adaptation is a critical quality indicator because marginal discrepancies may increase luting cement dissolution, plaque retention, microleakage, postoperative sensitivity, secondary caries and periodontal inflammation. Holmes et al. clarified the terminology of internal gap, marginal gap, vertical marginal discrepancy and absolute marginal discrepancy, emphasizing that different measurement definitions can lead to inconsistent interpretation across studies [3]. Although there is no universally accepted threshold for clinical acceptability, the classic work of McLean and von Fraunhofer suggested

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DOI: https://doi.org/10.3329/bjms.v25i20.91269

that marginal discrepancies around or below 120 µm may be clinically tolerable for complete coverage restorations [4]. Contemporary digital studies often report smaller mean values, but values depend on finish line design, scanning technique, cement spacer settings, material type, sintering shrinkage and measurement method.

Zirconia has become one of the most widely used prosthetic ceramics because of its high flexural strength, transformation toughening and favorable fatigue performance. CAD/CAM zirconia restorations, particularly monolithic forms, avoid veneering porcelain chipping and permit more conservative occlusal reduction than layered systems. Nevertheless, zirconia restorations undergo substantial volumetric shrinkage during sintering, and this step remains one of the most technique-sensitive phases of fabrication. Conventional sintering commonly requires several hours, whereas high-speed sintering protocols aim to complete the process within minutes, making chairside or same-day posterior zirconia restorations more feasible. The potential concern is whether accelerated heating and cooling compromise marginal adaptation, internal fit or mechanical reliability.

Previous in vitro studies have reported acceptable marginal and internal adaptation for CAD/CAM zirconia crowns, but results vary among systems and workflows [5-7]. Cement space settings, fabrication stages and cementation procedures can alter fit values, and investigations comparing different scanners or workflow sequences have shown that even small digital or laboratory variations may affect marginal discrepancies [8-12]. Recent evidence suggests that high-speed sintering may maintain or even improve marginal adaptation in selected zirconia systems, but the evidence remains material-specific and dependent on scanner, milling and furnace protocols [13]. Few studies simultaneously evaluate marginal adaptation, internal fit and fracture resistance after aging in a design that simulates posterior prosthodontic loading.

Therefore, the present in vitro study was designed to compare CAD/CAM monolithic zirconia crowns fabricated using conventional and high-speed sintering protocols, with lithium disilicate crowns used as a clinically established ceramic comparator. The primary objective was to evaluate marginal adaptation and internal fit using a standardized silicone replica technique. The secondary objective was to assess fracture resistance after thermomechanical aging. The null hypothesis was that there would be no significant difference among the three ceramic crown groups in marginal gap, internal gap or fracture resistance.

MATERIALS AND METHODS

Study design and sample allocation

This laboratory-based in vitro study was conducted in a prosthodontic research setting. A total of 45 complete-coverage posterior crowns were fabricated on standardized mandibular first molar dies. The sample size was estimated using marginal gap as the primary outcome, assuming a minimum detectable difference of 12 µm among groups, a pooled standard deviation of 10 µm, alpha of 0.05 and 80% power. Fifteen specimens per group were considered adequate. Specimens were allocated into three groups: Group I, conventionally sintered 4Y-TZP monolithic zirconia crowns (CS-Zr); Group II, high-speed sintered 4Y-TZP monolithic zirconia crowns (HS-Zr); and Group III, CAD/CAM lithium disilicate crowns (LD).

Die preparation and digital workflow

A mandibular first molar typodont tooth was prepared for a full-coverage crown with 1.2 mm axial reduction, 1.5 mm occlusal reduction, a 1.0 mm deep chamfer finish line and approximately 6 degrees of total occlusal convergence. The prepared tooth was duplicated using addition silicone and poured with epoxy resin to produce 45 identical dies. Each die was inspected under magnification to exclude marginal chips, voids and surface defects. All dies were scanned with the same optical scanner under standardized ambient light conditions.

A full-contour crown was designed using CAD software. The cement spacer was set at 50 µm beginning 1.0 mm above the finish line, with no spacer at the marginal collar. Standardized occlusal anatomy and proximal contours were maintained for all specimens. Zirconia crowns were milled from pre-sintered 4Y-TZP blocks using a five-axis milling machine. Lithium disilicate crowns were milled from partially crystallized CAD/CAM blocks according to the manufacturer's recommended parameters.

Sintering, crystallization and finishing

CS-Zr crowns were sintered using a conventional program with gradual heating, final temperature hold and slow cooling. HS-Zr crowns were sintered using the validated rapid program recommended for the same zirconia blank and furnace combination. Lithium disilicate crowns were crystallized and glazed in a ceramic furnace according to the manufacturer's instructions. After sintering or crystallization, crowns were examined under 10x magnification. Crowns with visible cracks, marginal chipping or incomplete seating were excluded and replaced before measurements. No internal adjustment was performed before fit evaluation.

Measurement of marginal and internal fit

Marginal and internal gaps were assessed using a silicone replica technique. Light-body polyvinyl siloxane was injected into each crown, which was then seated on its corresponding die under a constant vertical load of 50 N for five minutes. After setting, the thin replica layer was stabilized with heavy-body silicone. Each replica was sectioned buccolingually and mesiodistally, producing four segments for measurement. Marginal gap values were recorded at eight predefined marginal points per specimen, and internal gap values were recorded at axial and occlusal locations. Measurements were performed using a stereomicroscope at 40x magnification and calibrated image-analysis software. Two blinded examiners recorded measurements, and the mean of both readings was used for analysis.

Cementation, aging and fracture resistance

All crowns were cemented on their corresponding epoxy dies using dual-cure resin cement. The intaglio surfaces of zirconia crowns were airborne-particle abraded with 50 μm alumina at low pressure and cleaned ultrasonically; lithium disilicate crowns were etched with hydrofluoric acid, silanized and cemented. A constant seating load of 50 N was maintained during cement polymerization. Excess cement was removed before final curing.

Cemented crowns were stored in distilled water at 37°C for 24 hours and then subjected to 5000 thermocycles between 5°C and 55°C with a dwell time of 30 seconds. Mechanical aging was performed for 100,000 cycles at 100 N using a spherical stainless-steel antagonist contacting the central fossa. Fracture resistance was tested in a universal testing machine at a crosshead speed of 1.0 mm/min until catastrophic fracture or sudden load drop. Maximum load at failure was recorded in newtons. Failure mode was classified as repairable crown fracture, catastrophic crown fracture or die-associated fracture.

Statistical analysis

Data were analyzed using SPSS version 26.0. Normality was assessed using the Shapiro-Wilk test, and homogeneity of variance was assessed using Levene's test. One-way analysis of variance was used for normally distributed continuous variables, followed by Tukey's post-hoc test. Kruskal-Wallis analysis was planned for non-normally distributed variables, but all primary variables met normality assumptions. Categorical failure modes were compared using the chi-square test. Statistical significance was set at $p<0.05$.

RESULTS

All 45 crowns were successfully fabricated and included in the final analysis. No specimen showed visible marginal chipping, incomplete seating or pre-test fracture. Dimensional characteristics of the standardized dies and crowns are summarized in Table 1. There were no statistically significant differences among groups in die height, finish-line diameter, crown thickness or crown weight, confirming baseline comparability.

Marginal and internal fit outcomes are presented in Table 2. HS-Zr crowns demonstrated the lowest mean marginal gap (67.9 ± 8.7 μm), followed by LD crowns (76.4 ± 9.8 μm) and CS-Zr crowns (82.6 ± 10.9 μm). The difference among groups was statistically significant ($p<0.001$). Tukey's post-hoc analysis showed a significant difference between HS-Zr and CS-Zr ($p<0.001$), while the difference between HS-Zr and LD approached significance ($p=0.046$). All mean marginal gap values were below 120 μm.

Mean internal gap also differed significantly among groups ($p=0.002$). HS-Zr crowns showed the lowest mean internal discrepancy (91.8 ± 11.6 μm), followed by CS-Zr (103.5 ± 13.4 μm) and LD (112.7 ± 15.1 μm). Occlusal internal gaps were higher than axial gaps in all groups. Fracture resistance and failure patterns are shown in Table 3. Zirconia groups had significantly higher fracture resistance than lithium disilicate ($p<0.001$). CS-Zr showed the highest mean fracture resistance (2386.4 ± 286.7 N), followed by HS-Zr (2264.8 ± 254.3 N). The difference between the two zirconia groups was not statistically significant ($p=0.412$). Most zirconia specimens showed catastrophic crown fracture, while lithium disilicate demonstrated a higher proportion of repairable fractures.

Table 1. Baseline dimensional standardization of specimens

Parameter	CS-Zr (n=15)	HS-Zr (n=15)	LD (n=15)	p-value
Die axial height (mm)	5.82 ± 0.08	5.80 ± 0.07	5.81 ± 0.09	0.742
Finish-line diameter (mm)	10.41 ± 0.06	10.43 ± 0.07	10.40 ± 0.08	0.618
Occlusal crown thickness (mm)	1.53 ± 0.05	1.52 ± 0.06	1.55 ± 0.05	0.486
Axial crown thickness (mm)	1.15 ± 0.04	1.14 ± 0.05	1.16 ± 0.05	0.577
Crown weight (g)	0.84 ± 0.06	0.83 ± 0.05	0.79 ± 0.06	0.071

Values are presented as mean ± standard deviation. CS-Zr: conventionally sintered zirconia; HS-Zr: high-speed sintered zirconia; LD: lithium disilicate.

Table 2. Marginal and internal gap values

Outcome (µm)	CS-Zr	HS-Zr	LD	p-value
Mean marginal gap	82.6 ± 10.9	67.9 ± 8.7	76.4 ± 9.8	<0.001
Absolute marginal discrepancy	98.3 ± 13.6	82.1 ± 11.2	91.6 ± 12.7	<0.001
Axial internal gap	86.9 ± 10.8	78.5 ± 9.4	94.2 ± 12.8	0.003
Occlusal internal gap	120.1 ± 16.7	105.1 ± 14.3	131.2 ± 18.6	<0.001
Mean internal gap	103.5 ± 13.4	91.8 ± 11.6	112.7 ± 15.1	0.002

Values are presented as mean ± standard deviation. One-way analysis of variance with Tukey post-hoc testing was used.

Table 3. Fracture resistance and failure modes after aging

Parameter	CS-Zr	HS-Zr	LD	p-value
Fracture resistance (N)	2386.4 ± 286.7	2264.8 ± 254.3	1542.3 ± 214.6	<0.001
Minimum-maximum load (N)	1884-2826	1816-2679	1192-1894	—
Repairable crown fracture	1 (6.7%)	2 (13.3%)	6 (40.0%)	0.041
Catastrophic crown fracture	11 (73.3%)	10 (66.7%)	7 (46.7%)	0.186
Die-associated fracture	3 (20.0%)	3 (20.0%)	2 (13.3%)	0.851

Fracture resistance values are mean ± standard deviation. Failure modes are shown as frequency and percentage.

DISCUSSION

The present in vitro study rejected the null hypothesis for marginal gap, internal gap and fracture resistance. High-speed sintered zirconia crowns showed significantly lower marginal and internal gaps than conventionally sintered zirconia and lithium disilicate crowns, while both zirconia groups demonstrated substantially higher fracture resistance than lithium disilicate. The findings indicate that a validated rapid sintering protocol can produce posterior monolithic zirconia crowns with clinically acceptable adaptation and mechanical performance.

The marginal gap values observed in all groups were within the widely cited clinical acceptability range proposed in earlier prosthodontic literature [3,4]. However, the results also demonstrate that clinically acceptable values can still differ statistically among material-processing protocols. The lower marginal gap in the HS-Zr group may be attributed to more uniform thermal processing and reduced cumulative distortion during prolonged furnace cycles. Although conventional sintering is traditionally considered the reference method for zirconia, rapid sintering programs have evolved with material-specific heating rates and furnace calibration, which may limit uncontrolled shrinkage when used within the manufacturer's indications.

The present results are consistent with the broader literature showing that CAD/CAM zirconia crowns generally achieve acceptable marginal and internal fit when digital scanning, milling and sintering variables are controlled [5-7]. Rajan et al. observed that different CAD/CAM systems produce variable marginal and internal adaptation, reinforcing that fit is a workflow outcome rather than a material property alone [6]. Ji et al. similarly demonstrated acceptable marginal fit in anatomic contour zirconia systems, but measurement values were influenced by the system evaluated [7].

These observations support the standardized design used in the present study, where the cement spacer, scanner, software and die design were held constant to isolate the effect of material-processing protocol.

Cement space is an important determinant of adaptation. Inadequate internal relief may prevent complete seating of the crown, whereas excessive relief may increase cement thickness and compromise support. Studies on cement spacer settings and fabrication stages have shown that marginal fit can be modified by software parameters, sintering, glazing and cementation [8,9]. In the present study, the same 50 µm spacer was used in all groups and the marginal collar was kept unrelieved to avoid overcompensation at the finish line. The occlusal internal gap was greater than the axial gap in all groups, which is a common finding in CAD/CAM crowns and may reflect milling bur geometry, occlusal anatomy, data smoothing and limitations in reproducing sharp internal line angles.

The high fracture resistance of both zirconia groups confirms the suitability of monolithic zirconia for posterior full-coverage crowns under high occlusal demand. Although CS-Zr showed numerically higher fracture resistance than HS-Zr, the difference was not statistically significant. This finding suggests that high-speed sintering did not produce clinically meaningful weakening under the experimental conditions used. The lithium disilicate group demonstrated lower fracture resistance, but its mean value remained above typical posterior masticatory forces. Therefore, the clinical interpretation should not be that lithium disilicate is inadequate, but that zirconia provides a larger safety margin for posterior sites, bruxism-prone patients or limited restorative thickness.

The comparison with recent high-speed sintering research is clinically relevant. Lee et al. reported that high-speed sintering influenced marginal fit and suggested that rapid protocols could be promising for single-visit zirconia treatment when combined with digital measurement methods [13]. The present study supports this direction but adds fracture resistance data after thermomechanical aging. Nevertheless, the results should be interpreted within the limitations of an in vitro design. Thermal cycling and mechanical aging simulate selected aspects of oral function, but they cannot reproduce all intraoral variables such as pH fluctuation, saliva, parafunction, antagonist wear, cement degradation and long-term fatigue damage.

Measurement methodology also influences interpretation. Silicone replica assessment is conservative, reproducible and non-destructive, but it provides two-dimensional measurements at selected section points rather than complete three-dimensional surface mapping. Digital methods, including mesh superimposition and point-cloud analysis, may provide more comprehensive assessment, but they require validated alignment algorithms and careful segmentation [15]. Nawafleh et al. emphasized that measurement techniques for marginal adaptation vary substantially, which limits direct comparison of values across studies [17]. Future studies should combine replica methods with three-dimensional optical or micro-computed tomography techniques to improve comparability.

Another limitation is that only one zirconia material, one crown design and one high-speed sintering furnace protocol were tested. Zirconia microstructure, yttria content, translucency, shade, restoration thickness and furnace calibration may influence final shrinkage and mechanical properties. Clinical studies and systematic reviews of CAD/CAM prostheses show favorable survival, but long-term performance depends on more than initial fit; occlusal design, cementation protocol, periodontal maintenance and patient-related loading patterns are also important [18]. Therefore, the results should not be generalized to all zirconia systems or all rapid sintering programs without further validation.

Within these limitations, the study has several strengths. It used standardized dies, a single digital design, fixed cement spacer parameters, blinded measurement and aging before fracture testing. [19-22] By including lithium disilicate as a comparator, the study provides a clinically meaningful context for interpreting fracture resistance. The results suggest that high-speed sintered zirconia can be incorporated into same-day posterior prosthodontics, provided that clinicians avoid arbitrary sintering modifications and use material-furnace combinations supported by manufacturer and independent validation.

CONCLUSION

Within the limitations of this in vitro study, CAD/CAM monolithic zirconia crowns fabricated using a validated high-speed sintering protocol demonstrated superior marginal and internal adaptation compared with conventionally sintered zirconia and lithium disilicate crowns. Both zirconia groups exhibited significantly higher fracture resistance than lithium disilicate after thermomechanical aging, and the difference between conventional and high-speed zirconia was not statistically significant. All tested crowns achieved mean marginal gap values within clinically acceptable limits.

High-speed sintering may therefore be considered a promising option for single-visit posterior zirconia crowns when the workflow is standardized and material-specific instructions are followed. Future research should include multiple zirconia formulations, longer fatigue protocols, micro-computed tomography assessment, cement degradation analysis and controlled clinical follow-up to confirm the long-term implications of accelerated sintering in prosthodontic practice.

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