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Conventional and Modified Veneered Zirconia vs. Metal Ceramic: Fatigue and Finite Element Analysis

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Abstract

Purpose: The purpose of this study was to test the hypothesis that all-ceramic crown core-veneer system reliability is improved by modifying the core design and as a result is comparable in reliability to metal-ceramic retainers (MCR). Finite element analysis (FEA) was performed to verify maximum principal stress distribution in the systems.
Materials and Methods: A first lower molar full crown preparation was modeled by reducing the height of proximal walls by 1.5 mm and occlusal surface by 2.0 mm. The CAD-based preparation was replicated and positioned in a dental articulator for specimen fabrication. Conventional (0.5 mm uniform thickness) and modified (2.5 mm height, 1 mm thickness at the lingual extending to proximals) zirconia (Y-TZP) core designs were produced with 1.5 mm veneer porcelain. MCR controls were fabricated following conventional design. All crowns were resin cemented to 30-day aged composite dies, aged 14 days in water and either single-loaded to failure or step-stress fatigue tested. The loads were positioned either on the mesiobuccal or mesiolingual cusp ($n = 21$ for each ceramic system and cusp). Probability Weibull and use level probability curves were calculated. Crack evolution was followed, and postmortem specimens were analyzed and compared to clinical failures.
Results: Compared to conventional and MCRs, increased levels of stress were observed in the core region for the modified Y-TZP core design. The reliability was higher in the Y-TZP-lingual-modified group at 100,000 cycles and 200 N, but not significantly different from the MCR-mesiolingual group. The MCR-distobuccal group showed the highest reliability. Fracture modes for Y-TZP groups were veneer chipping not exposing the core for the conventional design groups, and exposing the veneer-core interface for the modified group. MCR fractures were mostly chipping combined with metal coping exposure.
Conclusions: FEA showed higher levels of stress for both Y-TZP core designs and veneer layers compared to MCR. Core design modification resulted in fatigue reliability response of Y-TZP comparable to MCR at 100,000 cycles and 200 N. Fracture modes observed matched with clinical scenarios.

Yttria-tetragonal zirconia polycrystals (Y-TZP) have been regarded as the most fracture resistant substructure ceramic material for crowns and fixed partial dentures (FPDs).[1,2] Y-TZP's high mechanical properties and transformation toughening at the crack tip have motivated its extensive evaluation in several clinical studies involving esthetic regions and FPDs,[3] whereas less attention has been devoted to Y-TZP-supported crowns at posterior regions. Although Y-TZP substructures show high survival rates, chipping and fractures of the veneering porcelain have raised concerns about the long-term success of Y-TZP-supported all-ceramic reconstructions.[4,5]

Clinical results conflict, with some indicting an absence of porcelain failures of Y-TZP-supported restorations[6–8] while others indicate high porcelain failure rates.[4,5,9] Engineering

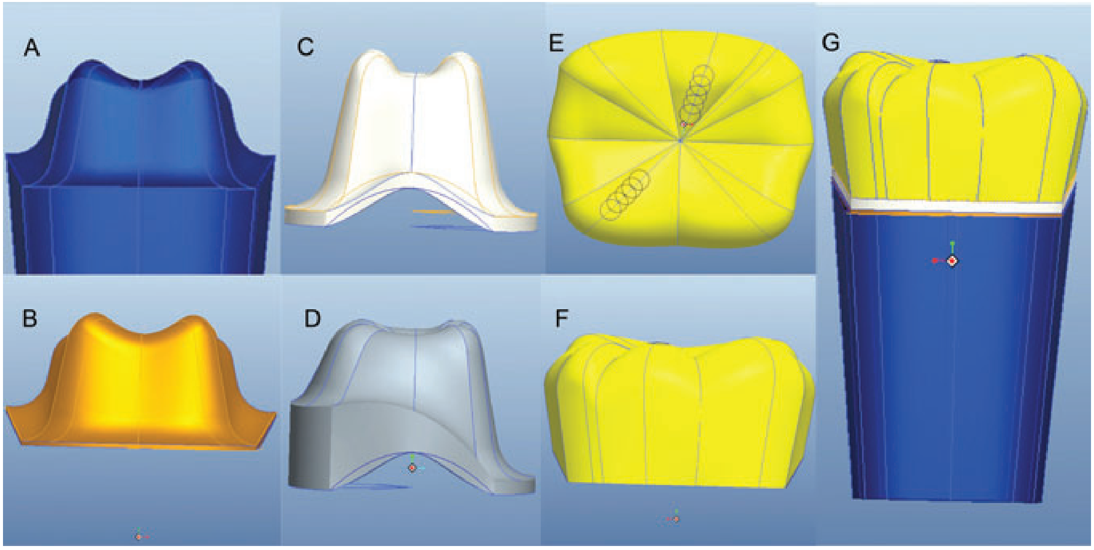

Figure 1 CAD-designed components: (A) tooth preparation buccal view, (B) cement layers buccal view, (C) standard core proximal view, (D) modified core proximal view, (E) veneer occlusal view, (F) veneer buccal view, and (G) veneer/core assembly buccal view. All simulations were carried out by load application over (E) a 1 mm diameter area on the distobuccal cusp or mesiolingual cusp. Note the modification of the core (D) and the sliding contact toward to the central fossa (E).

parameters and their relationship to clinical longevity deserve further investigation.[10] For instance, in an attempt to improve clinical performance of all-ceramic layered structures, core designs reinforcing the centric holding cusps have been attempted and are based on empirical metal ceramic restoration (MCR) work from the 1980s.[11-14] These anecdotal and empirical substructure design modifications have not been appropriately tested in controlled settings. Similarly, attempts to improve FPD[6,8] longevity have not been verified in the laboratory.

MCRs[15,16] are considered the standard treatment in dentistry due to their high success rate.[17] In contrast to all-ceramic restorative systems, biological issues are more commonly emphasized in MCRs, and technical complications such as porcelain chipping/fractures are rarely described.[18] While higher clinical longevity has been reported in MCRs, if both mechanical and thermal stresses are better controlled through design and processing methods, all-ceramic systems should be able to achieve similar clinical performance.[19] Since laboratory simulation has been shown to be effective in mimicking clinical fracture patterns for both all-ceramic and MCRs in both centric and noncentric holding cusps,[20] comparison between material systems, processing variations, and core-veneer designs can be achieved, allowing an informed design rationale for future crown systems.

This investigation used finite element analysis (FEA) to evaluate stress distribution on Y-TZP-supported and MCR restorations under simulated load. Then, sliding contact fatigue testing explored the following hypotheses: (1) all-ceramic crown reliability is improved by core design modification and comparable to MCR; (2) higher reliability is expected whenever sliding contact is performed on distobuccal cusps compared to mesiolingual cusps of mandibular first molar crowns.

Table 1 Input properties for FEA

Material	Young's modulus	Poisson's ratio
Porcelain	70 MPa	0.24
Y-TZP	210 MPa	0.23
Cement	5 GPa	0.30
Ag-Pd	92 GPa	0.33
Composite (dentin layer)	16 GPa	0.33

Materials and methods

Computer modeling for FEA

An anatomically correct 3D prototype of a mandibular first molar full crown preparation was modeled by reducing proximal walls by 1.5 mm and occlusal surface by 2.0 mm using CAD software, and a bilayer all-ceramic crown was generated (Pro/Engineer Wildfire, PTC, Needham, MA). The solid components of the tooth/all-ceramic crown system were created in CAD software (Pro/Engineer Wildfire) and comprised of: a veneer layer (porcelain), a uniform 0.5 mm thickness crown substructure layer, or a modified substructure design with an overall 0.5 mm thickness with 1 mm thickness and 2.5 mm height added at the lingual flange and extending to both proximals, a 100 μm thick cement layer (resin cement), and a tooth preparation (dentin) component (Fig 1). The components were assembled, imported into FEA software (Pro/Mechanica, PTC), meshed ($\sim$16,000 tetrahedral elements), and tested for convergence prior to mechanical simulation. Material properties are presented in Table 1.

The following assumptions were included in the FEA model: (1) all solids were homogeneous, isotropic, and linear elastic;

(2) no slip conditions (perfect bonding) between components; (3) uniform 100 μm thick cement layer; (4) absence of flaws in all components; (5) 6 degrees of freedom (full) constraint on the root component surface. For the mesiolingual loading mechanical simulation, a 110 N vertical load plus a 200 N horizontal load toward the central fossa direction was applied over a 1 mm diameter circle at the mesiolingual cusp ridge on the veneer solid. For the distobuccal loading mechanical simulation, a similar load was applied at the distobuccal cusp ridge on the veneer solid. Simulations were conducted on the mesiolingual and distobuccal aspects of both all-ceramic and MCR configurations. The maximum principal stresses (MPS) for the core and veneer layers were recorded for both standard and modified models.

Single load to failure (SLF) and sliding-contact step-stress fatigue (SCSSF)

The CAD file of the prepared tooth dimensions described above was imported to a milling machine to generate plastic models. These models were replicated in epoxy and placed on a dental articulator with opposing dentition. Impressions of the replicated models and adjacent and opposing teeth were taken (Aquasil, Dentsply, York, PA) for crown fabrication. Pd-Ag alloy (Pd-Ag White Porcelain Alloy, Jensen Industries, North Haven, CT) substructures (0.5 mm thick) were fabricated and assigned to two groups according to the load application location determined as MCR-distobuccal (n = 21) and MCR-mesiolingual (n = 21). Y-TZP substructure (core) systems (LAVA, 3M/ESPE, St. Paul, MN) were milled in the presintered stage, and then fully sintered to achieve an even 0.5 mm thickness (conventional design). A modified core with 2.5 mm height in proximal regions and 1 mm thickness at the lingual aspect was also fabricated (Fig 2).

The three Y-TZP groups were designated according to the core design (conventional or modified) and load application location (distobuccal cusp loading or mesiolingual cusp loading) designated as Y-TZP-distobuccal conventional (n = 21); Y-TZP-mesiolingual conventional (n = 21), and Y-TZP-mesiolingual modified (n = 21). All groups were hand-layer veneered with a matching coefficient of thermal expansion (CTE) porcelain system (Creation Porcelain, Jensen Industries; LAVA Veneer, 3M/ESPE, respectively) following manufacturers' directions [CTE values were: LAVA Veneer = 10.0, Zirconia LAVA = 10.4, Porcelain veneer for MCR groups = 13.6 (opaque) and 12.0 (dentin) and MCR copings (Pd-Ag) = 14.5].[21] The standardization of the thickness and anatomy of the veneering ceramic was accomplished with a silicone index made from an impression of the waxed desired anatomy. One silicone index was used for fabrication of all specimens. Final crowns presented appropriate marginal fit (checked by probing and visual inspection) and standardized occlusal morphology.

Composite (Z100, 3M/ESPE) dies (n = 105) were fabricated from silicon rubber impressions (Aquasil) of the machined plastic model. The dies were stored in distilled water at 37°C for 30 days to assure complete water uptake dimensional expansion.[22]

All crowns were cemented (RelyX Unicem, 3M/ESPE) under a 10 N load following manufacturer's instructions. The cemented crowns were vertically embedded in acrylic resin (Orthoresin, Degudent, Main, Germany) and poured in a 25 mm diameter plastic tube, leaving buccal, lingual, and proximal cervical margins evenly exposed 2 mm above the potting surface.

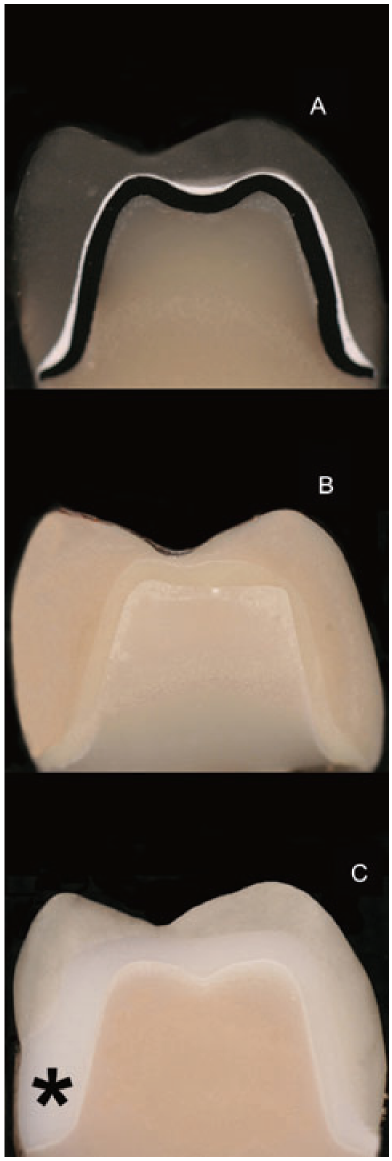

Figure 2 Cross-sectional view of specimens (A) MCR, (B) Y-TZP conventional, and (C) Y-TZP modified (asterisks).

After cementation procedures, the specimens were incubated in distilled water for at least 7 days before mechanical testing. Three crowns of each group underwent SLF testing at a 1 mm/min crosshead speed using a universal testing machine (INSTRON 5666, Canton, MA) with a 6.25 mm diameter tungsten carbide (WC) ball. Based upon the mean load to failure from SLF, three SCSSF profiles were determined following a 3:2:1 ratio for the groups (mild, moderate, and aggressive, respectively).[23] An SCSSF test was performed on each group at 2 Hz using an electrodynamic testing machine equipped with

Table 2 Highest maximum principal stress (MPS) for veneer and core in the model groups

Groups	Veneer (MPa)	Core (MPa)
Y-TZP-mesiolingual-conventional	705	451
Y-TZP-mesiolingual modified	726	662
Y-TZP-distobuccal- conventional	702	420
MCR- distobuccal	294	590
MCR- mesiolingual	368	590

a 6.25 mm diameter WC ball (ELF 3300, EnduraTec Division, Bose Corporation, Minetonka, MN) until failure or survival.[23] During fatigue, the WC indenter slid 0.7 mm downward on the cusp incline toward the central fossa. Failure was defined as cohesive chipping of the veneer, extensive cracking of the veneer, or fracture of the porcelain exposing the core, whichever occurred first.

Use level probability Weibull calculations using a cumulative damage power law relationship were performed (Alta Pro 7, Reliasoft, Tucson, AZ).[24] Reliability (90% 2-sided confidence bounds) for completion of 100,000 cycles at a 200 N load was also calculated for group comparisons. If the Weibull use level probability calculated Beta was <1 for any group, then a Weibull two-parameter probability multi-plot (reliability vs. load) and contour plot (Beta vs. Eta) was plotted, eliminating the number of cycles from the analysis.

During mechanical testing, specimens were evaluated in a stereomicroscope under polarized light mode (MZ-APO stereomicroscope, Leica Microsystems Ltd., Heerbrugg, Switzerland) at the completion of each fatigue step for crack initiation/propagation. Criteria for failure involved porcelain veneer fracture/chip with or without substructure exposure, and bulk fracture.[25]

Results

FEA

The MPS recorded in the simulated models of the Y-TZP cores and veneers, and MCR are shown in Table 2. Regardless of all-ceramic core design, high stress levels were observed directly below the load region for both veneer and Y-TZP core solids, and higher stress levels were observed at the Y-TZP core region in contact with the cement layer. Substantially higher stress values at the core layer were observed for the modified core design. Compared to MCR, higher levels of stress were observed for both all-ceramic designs in both core and veneer layers.

SLF and SCSSF

The SLF mean value (n = 3) for MCR groups was 2002 ± 597 N, and for Y-TZP groups was 1220 ± 220 N. The mean values of both systems were used as a reference for step-stress profile development.

The step-stress use level Weibull probability was calculated with 90% confidence bounds for 100,000 cycles at a 200 N load

Table 3 Experimental groups reliability

Groups	Reliability	100 k cycles @ 200 N	Best fit – QCP
MCR-distobuccal	Upper	0.99	Exponential
	R	0.99	
	Lower	0.98	
MCR-mesiolingual	Upper	0.90	Weibull
	R	0.77	Cumulative damage
	Lower	0.51	Beta = 1.1
Y-TZP-distobuccal	Upper	0.49	Weibull
conventional	R	0.23	Cumulative damage
	Lower	0.04	Beta = 1.7
Y-TZP-mesiolingual	Upper	0.21	Weibull
conventional	R	0.04	Cumulative damage
	Lower	0.00	Beta = 2.4
Y-TZP-mesiolingual	Upper	0.97	Weibull
modified	R	0.91	Cumulative damage
	Lower	0.72	Beta = 6.4

(Table 3). An exponential fit was used for the MCR-distobuccal group where fatigue across the profiles used had no influence on the fracture behavior ($\beta < 1$). For the MCR-mesiolingual group, the β value of 1.1 showed that failure did not vary over time (number of cycles). For the remaining groups, β values of 1.7 (Y-TZP-distobuccal-conventional), 2.4 (Y-TZP-mesiolingual-conventional) and 6.4 (Y-TZP-lingual modified) indicated that the failure rate increased over time due to damage accumulation.

The MCR-distobuccal group presented the highest reliability (100,000 cycles at 200 N) among all groups, and no significant differences were observed between Y-TZP-mesiolingual-modified and MCR-mesiolingual groups (Table 2). Significantly lower reliability levels were observed for both mesiolingual and distobuccal Y-TZP-conventional design groups (Table 2).

Load to failure data for each specimen of all five groups were then used to calculate probability Weibull distributions (Weibull 7++, Reliasoft) (Fig 3A). A probability Weibull two-parameter multiplot (reliability vs. load) showed Weibull modulus for MCR-distobuccal-β = 4.9 (3.7-6.5),[26] MCR-mesiolingual-β = 2.8 (2.0-3.9), Y-TZP-distobuccal-conventional-β = 3.3 (2.3-4.7),[26] Y-TZP-mesiolingual-conventional-β = 6.2 (3.6-10.5), and Y-TZP-mesiolingual-modified β = 5.5 (3.0-10.0).[27] The MCR-distobuccal group presented significantly higher characteristic failure load (Eta) (±90% CI) = 1304 (1216-1401) than all other groups. Characteristic failure load values were 370 (332-414) for Y-TZP-distobuccal-conventional, 273 (240-311) for Y-TZP-mesiolingual-conventional, 631 (566-704) for Y-TZP-mesiolingual modified, and 984 (875-1108) for MCR-mesio-lingual. A contour plot is presented in Fig 3B.

The chief failure modes for Y-TZP groups were chipping, cohesive within the veneer, for the conventional design groups, and exposing the veneer core interface for the modified group. While failures were confined within the cusp bulk for the modified core design, failures involving the lingual cusp extended to proximal areas on the conventional core design. MCR groups'

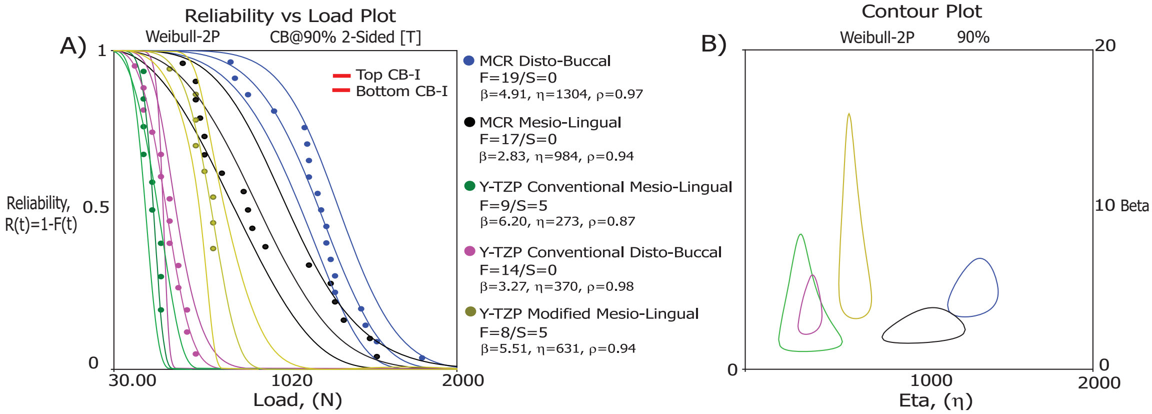

Figure 3 Weibull two-parameter probability (A) multi-plot (reliability vs. load) and contour plot (B). MCR buccal indicates significantly higher reliability, position of the Y-TZP-conventional distobuccal and mesiolingual groups to the left indicate significantly lower reliability, and the overlap (two-sided 90% confidence bounds) between groups Y-TZP-modified (yellow data points in A) and MCR mesiolingual group (black points) indicate no significant difference in reliability. In (B) there was overlap only between Y-TZP-conventional groups. The MCR distobuccal group showed the highest Eta. The Y-TZP-modified mesiolingual group presented significant improvement compared to Y-TZP-conventional groups.

failures comprised veneer layer fractures exposing the metal core (Fig 4).

Discussion

Y-TZP has been considered as a potential replacement for metal substructures in dental restorations due to its excellent mechanical properties and biocompatibility.[28,29] However, Y-TZP-supported restorations have shown early porcelain veneer failures.[4,5,30,31] Previous investigations suggest that porcelain veneer failures in Y-TZP-based all-ceramic restorations may originate due to several factors, including lack of porcelain support,[8,11,30] differences in the CTE between core and veneer,[9,32] processing techniques,[9] the unknown implications of phase transformation,[33] and the low thermal diffusivity of Y-TZP compared with alumina and metal.[19]

The present investigation addressed the effect of core design modification in an attempt to improve porcelain veneer support in an anatomically designed Y-TZP mandibular molar crown and consequently their reliability relative to MCR crowns. The computer simulation results showed a stress distribution shift from the veneer to the core layer when the modified core design was compared to the conventional design. Since the models were linear elastic, stress concentration regions would be the same for whichever load magnitude is applied to the system, and although loads encountered in single load to fracture were applied, lower loads more commonly observed during function would present the same relative stress concentration pattern with lower magnitude. While increased stress levels were observed for the modified design on the mesiolingual cusp, this group presented higher reliability during laboratory mechanical testing compared to both mesiolingual and distobucal cusps of the conventional design crowns. Such a discrepancy may be due to a flaw distribution effect, since lower porcelain volumes were present for the modified design compared to the conventional design. Thus, caution must be observed in extrapolating simulation data in ceramic materials in simplified systems like the ones used in this study (no assessment and/or inclusion of flaw population addressed). Also, the present study did not consider thermal processing effects on stress distribution, further limiting the mechanical simulation models.

According to the SCSSF results, significantly lower reliability (and damage accumulation as per $\beta > 1$ for both groups) was found for the Y-TZP groups relative to MCR crowns at both cusp inclines; however, reliability was significantly changed by the core design modification, and the performance was comparable to MCR levels with mesiolingual cusp sliding loads. Relative to the significantly higher reliability presented by MCR on the distobuccal cusp, we speculate that the combination of porcelain thickness and the lower core elastic modulus, along with the high thermal diffusivity during processing, likely allowed lower degrees of surface and internal residual stresses, possibly suppressing crack initiation and propagation (supported by the $\beta < 1$, which suggests that no consistent damage accumulation occurred, and failure was governed by the system failure load).

Our results also indicate that the location of applied load may also affect both systems' reliability. It has been speculated that the higher fracture potential of nonfunctional cusps in mandibular molars is related to their anatomical shape. Nonfunctional cusps are narrower, and the angular inclinations of these cusps are smaller than the functional cusps. Thus, they are more susceptible to the horizontal loading component.[34,35] These previous observations are supported by our results, considering the mesiolingual cusp of the Y-TZP system tested, as a significant increase in reliability and fractures of decreased size were observed with the modified design cusp support.

In addition, the high loads used in this study may alter the ratio of thermally and mechanically induced stresses from the ratio that would occur in a clinical scenario. This fact could change the reliability model and therefore needs careful interpretation; however, despite the high load conditions employed

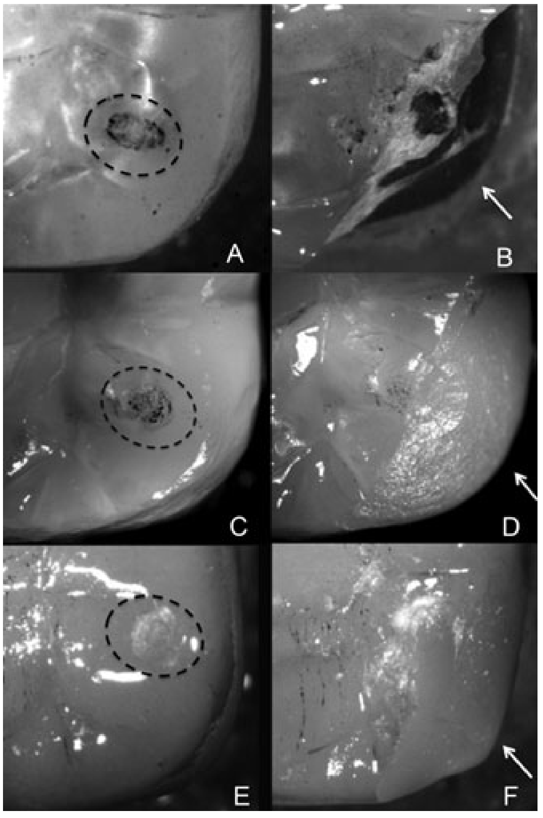

Figure 4 Fracture modes for MCR groups (A-B), Y-TZP Conventional groups (C-D), and Y-TZP modified group (E-F). Occlusal views of the indentation area (dotted circles) where the fracture initiated and propagated toward the margins and proximal areas (arrows) showing fracture of the porcelain veneer.

in this study, the SCSSF test led to failure modes similar to those observed clinically, suggesting the effectiveness of the method employed for the direct comparison of crown systems of differing configurations.

The stiff contact generated by the WC ball may produce a more concentrated stress, potentially leading to different failure mechanisms compared to a lower modulus indenter such as enamel or porcelain; however, concentrated load testing as conducted here has been shown to produce clinically relevant fractures.[20,26,36,37] At the point of loading, contact pressure increases monotonically with an expanding contact circle,[38,39] which is actually related to indenter radius. In Hertzian contact, the elastic modulus of the indenter only enters the calculations as it relates the contact area to the load applied.[38,39] Bhowmick et al[40] investigated the role of indenter modulus on cone crack evolution and compared, among others, a glass indenter to WC indenter loaded on glass substrates. Bhowmick et al's study showed a 40% decrease in load to cone cracking when the WC was used instead of the glass indenter. Glass-on-porcelain testing leads to high friction forces, leading to partial cone cracking. WC on porcelain, while having higher contact pressure, has a lower coefficient of friction, particularly after a few cycles. Currently the authors of the present study are conducting fatigue contact damage studies using anatomically correct ceramic crowns comparing WC, glass, and Steatite ball indenters. It is acknowledged that besides geometric alterations, results may be influenced by systems' thermal history during fabrication.[25] Thus, further studies exploring different veneer-core thermal processing along with geometric modifications are strongly recommended.

Conclusion

FEA showed that compared to MCR, Y-TZP showed higher levels of stress for Y-TZP core and veneer layers in both Y-TZP designs. For the fatigue investigation the following hypotheses were explored: (1) all-ceramic crown reliability is improved by core design modification and comparable to MCR under step-stress fatigue conditions; (2) higher reliability is expected whenever sliding contact fatigue is performed on buccal cusps compared to lingual cusps of the mandibular first molar. Since the applied design modification improved the reliability at 100,000 cycles at 200 N of the Y-TZP group, our first hypothesis was accepted. The second hypothesis was partially accepted, given the comparable reliability observed between lingual and buccal groups in the conventional core design Y-TZP group.

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