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# Lifetime prediction of zirconia and metal ceramic crowns loaded on marginal ridges

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## ABSTRACT

**Objective.** To evaluate the fatigue life of zirconia-veneered and metal-ceramic crowns comprised by an even thickness or a modified framework design when loaded on marginal ridges.

**Methods.** Eighty marginal ridges were present after fabrication of forty molar crowns cemented onto composite-resin replicas and divided ( $n=20$ /each), in the following groups: metal-ceramic with even thickness (MCev) or with a modified framework design (MCm, lingual collar with proximal struts); porcelain-fused to zirconia with even thickness (PFZev) or with the modified framework design (PFZm). Each marginal ridge (mesial and distal) was subjected to cyclic loading separately with a lithium disilicate indenter for  $10^6$  cycles or until fracture. Kruskal-Wallis and Wilcoxon matched pair test ( $p<0.05$ ) evaluated both marginal ridges. Every 125,000 cycles, the test was interrupted for damage inspection. Weibull distribution (90% confidence bounds) determined the probability of survival (reliability).

**Results.** Weibull 2-parameter contour-plot showed significantly higher fatigue life for PFZev compared to MC, and comparable with PFZm. A significant decrease in reliability was observed between groups from 625,000 until  $10^6$  cycles. Metal-ceramic groups presented significantly lower probability of survival at  $10^6$  cycles (MCev = 0.66% and MCm = 4.73%) compared to PFZm (23.41%) and PFZev (36.68%). Fractographic marks showed a consistent fracture origin and direction of crack propagation. Reliability was higher for porcelain-fused to zirconia than for metal ceramic crowns, regardless of framework design.

**Significance.** Zirconia-veneered crowns presented decreased fracture rates compared to metal ceramics, even when loaded at marginal ridges, regardless of framework design.

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### Keywords:

Zirconia

Fatigue

Metal ceramic

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## 1. Introduction

All-ceramic materials continue to be investigated in both laboratory and clinical settings in a constant quest to accumulate supportive data for their safe use. In general, these materials are still prone to fractures of multiple nature including bulk fractures or chipping within the veneering porcelain [1–5] given their inherent brittleness. The most common complications include veneering material fractures, loss of retention, endodontic treatment, and bleeding on probing. However, for crown applications and material such as porcelain fused to zirconia, it seems that the rates of such complications are comparable to those of metal ceramics, according to a recent systematic review [6]. Yet, such observations have been made on a relatively small number of studies, seldom of randomized controlled design that warrants further investigation in the field.

It is unequivocal that inconsistencies are present in reporting the extent of failures occurring clinically in all-ceramic materials, even when standardized evaluation systems are used (e.g., USPHS), which eventually results in uncertainties upon decision making towards replacement or repair for continued function [7]. In spite of its extension, a finding of clinical significance comprises where the failure is located. When at any free surface area (e.g., buccal, lingual or occlusal) access for repair is straightforward and may allow for successful repair. However, when at the proximal areas, not only access, but proper isolation may be hindered by adjacent teeth. Interestingly, a clinical study has shown that when occlusal contacts are present on mesial or distal ridges, fractures in porcelain-fused to zirconia prostheses demand restoration/replacement due to their extension leading to esthetics and/or function impairment [8].

Because the marginal ridges are a common location for occlusal contacts in natural dentition in maximal intercuspatation, regardless of Angle occlusal scheme (class I, II, and III), it is speculated that such areas may be more prone to failures when compared to contacts at the central fossa [9]. Finite element analysis investigations evaluating the stresses in marginal ridges and proximal areas have shown a high tensile stresses specially in molars [10] and second premolars [11,12].

The prevalence of contacts between the cusp and marginal ridge is 34.60% [13]. It may be present at only one marginal ridge [13,14] or two simultaneously [13]. Teeth that have the widest range of these contacts are the first molars, presenting up to six simultaneous occlusal contacts [15–17]. Furthermore, one to three contacts are common at molars [16] in intercuspal position. The explanation for this variety is given by the largest occlusal surface compared to other teeth [18].

Factors associated with failure rates of porcelain fused to polycrystalline zirconia crowns are multifaceted and attempts to reduce failures include modification of core design [19–22], improved CTE matching between core and porcelain [23–25], cooling rate of the porcelain [25,26], and others. By core design modification, an additional support for veneering ceramic is provided when compared to the standard design core with implications including an increase in probability of survival and a reduction in the extent of porcelain veneer frac-

ture [27,28]. However, virtually all investigations simulate the occlusal contact at the cusp inclines where the lingual collar provided additional support, rather than on marginal ridges where some failures have shown to occur clinically [7,29–45]. Therefore, whether failure rates can be decreased or not at the marginal ridges when a framework is designed to improve support is yet to be investigated.

The present study sought to investigate the fatigue life and failure modes of porcelain fused to zirconia (Y-TZP—yttria-stabilized tetragonal zirconia polycrystal) and metal-ceramic crowns with an even thickness or a modified framework design. The following null hypotheses tested were that fatigue life would not be improved: (1) by framework design modification and (2) by material used to fabricate crowns.

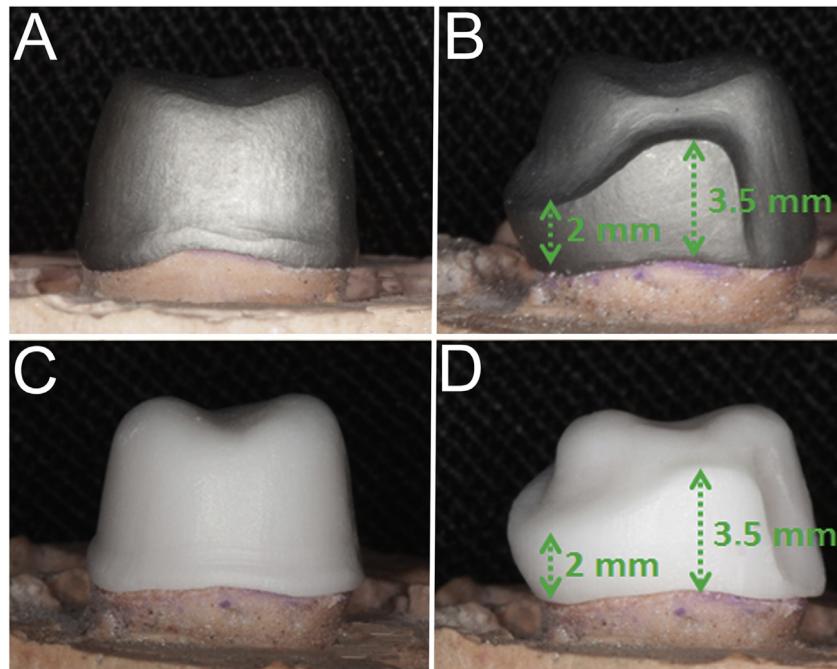
## 2. Materials and methods

An artificial mandibular first molar was positioned in a mannequin for full crown preparation that included 2.0 mm occlusal reduction, 1.5 mm axial reduction and a 1.2 mm shoulder margin with rounded internal angles [21]. Replicas of the prepared tooth ( $n=40$ ) were obtained by an impression with polyvinyl siloxane material (Express—3M Oral Care, St. Paul, MN, USA) followed by incremental packing and light-curing (Ulralux, Dabi Atlante, Ribeirão Preto, SP, Brazil) of composite resin (Z100, 3M Oral Care, St. Paul, MN, USA). These replicas were stored into a distilled water recipient for 30 days to provide hygroscopic expansion and minimize dimensional alteration [21,46]. The replicas were removed from the recipient, vertically positioned into a polyvinyl siloxane matrix (Express—3M ESPE) to standardize embedding and pouring of acrylic resin (Jet, Clássico Artigos Odontológicos, São Paulo, SP, Brazil) in a 25 mm diameter PVC tubes.

Replicas were randomly assigned to two groups ( $n=20$  each) according to the crown system used; metal ceramic (MC) or porcelain fused to zirconia (PFZ). Subsequently, each group was subdivided ( $n=10$  each) according to framework design comprising either a core with an even thickness (MCev and PFZev) or a modified design (MCm and PFZm). The even thickness groups presented a 0.5 mm thickness coping (Fig. 1A and C) and the modified core design comprised a 0.5 mm even thickness with a 1 mm thick lingual collar and 2.0 mm of height, connected to proximal struts of 3.5 mm height (Fig. 1B and D) [19,21,26].

For fabrication of MC crowns, an impression of each composite resin replica was made (Pentamix—3M Oral Care, St. Paul, MN, USA) with polyether material (Impregum F—3M Oral Care, St. Paul, MN, USA) and poured, resulting in a total of 20 stone dies. The even thickness and modified metal cores (cobalt-chromium, Fit Cast Cobalto, Metal Talmax, Curitiba, PR, Brazil) were manufactured by means of lost wax technique and cast according to manufacturer. The IPS d.SIGN Transpaneutral (Ivoclar Vivadent AG, Schaan, Liechtenstein) veneering ceramic was hand layered and the firing schedule followed the manufacturer's recommendation. The veneering ceramic transparency was chosen to facilitate crack inspection throughout fatigue cycles.

The Y-TZP cores (IPS e.max ZirCAD—Ivoclar Vivadent AG, Schaan, Liechtenstein) were milled from pre-sintered



**Fig. 1 – Proximal view of metal ceramic even thickness (A) and modified core designs (B) and porcelain fused to zirconia even thickness (C) and modified (D) groups and their respective dimensions.**

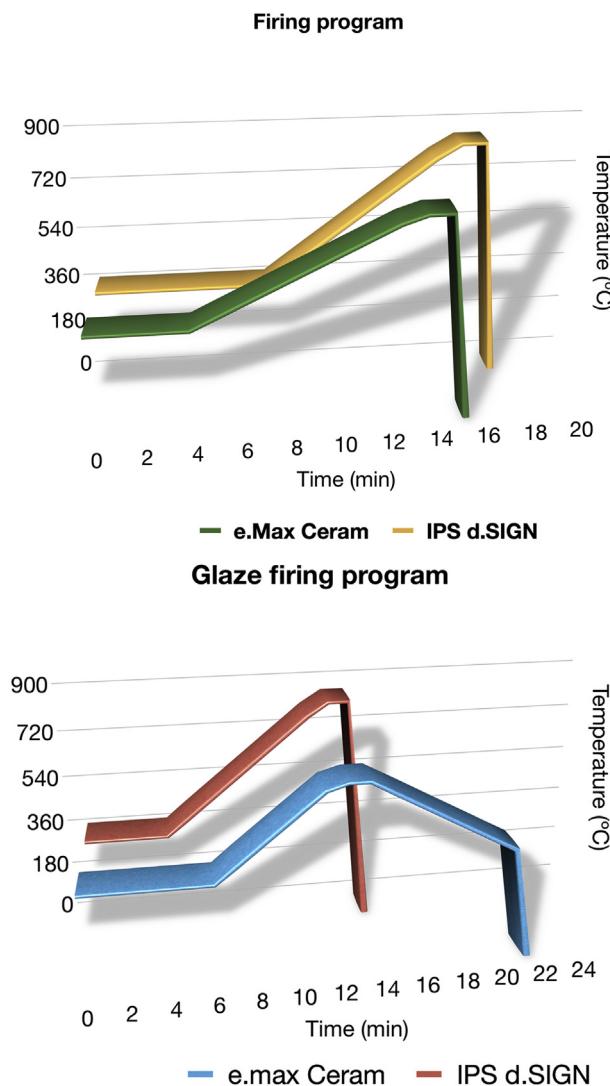
e.max ZirCAD blocks (shade MO 0 and block size 15C) in a CAD/CAM system (Cerec InLab, Sirona Dental System, Bensheim, Germany). The prepared tooth received a contrast layer (IPS Contrast Spray—Ivoclar Vivadent AG, Schaan, Liechtenstein) to allow its digital scanning (InEos Blue Desktop Scanner). The software (Cerec Software 4.0) created a 3D core image with 0.5 mm thickness (PFZev). To obtain the PFZm files for milling, the prepared tooth image saved in the software was correlated with the coping and preparation of the MCm group positioned on it for scanning. The correlation option of the software was performed to create the 3D image of PFZm core. After milling, the cores were sintered in the Sintramat furnace at 1500 °C for 8 h. The IPS e.max Ceram Transpacer (Ivoclar Vivadent AG, Schaan, Liechtenstein) veneering ceramic was hand layered according with the manufacturer's recommendations. The PFZ veneering porcelain and glaze firing schedule is presented in Fig. 2.

A gypsum matrix of the occlusal surface of a molar tooth was fabricated and fixed on a verticulator in order to standardize the occlusal anatomy during porcelain veneering. Porcelain thickness was 1.0 mm on the axial walls, 1.5 mm on the occlusal surface (Fig. 3A). No internal adjustments were necessary for any crowns on prepared composite resin replicas. Crowns were glazed and the MC group had the intaglio surface sandblasted with 240 mesh alumina, cleaned by sonicating in ethanol and air dried. The PFZ groups had their cementation surface cleaned with 35% phosphoric acid (Ultra-Etch, Ultradent, South Jordan, USA) for 60 s and then rinsed with water for 30 s. All crowns were cemented on the composite resin replicas with a self-adhesive resin cement (RelyX U200-3 M Oral Care, St. Paul, MN, USA) under a 50 N static occlusal load for 10 min. Samples were stored in 37 °C distilled water between 24–48 h before testing. Consequently, the

marginal ridges (mesial and distal) of each group ( $n = 20$ ) were obtained from the crown fabrication.

The fatigue equipment (Model MSFM – Elquip – São Paulo, SP, Brazil) delivered r-ratio cyclic loading without lateral movement at a 30–300 N load range for  $10^6$  cycles at 2 Hz until failure or suspension, under distilled water at 37 °C ( $\pm 2$  °C) [26]. Loading was applied at the marginal ridges of the occlusal surface with a spherical glazed monolithic lithium disilicate (IPS e.max Press HT High Translucency – Ivoclar Vivadent – Schaan/Liechtenstein) indenter of 3.18 mm radius, positioned in contact with marginal ridges, which was replaced every 500,000 cycles. Fatigue loading was initiated on the mesial marginal ridge until failure or  $10^6$  cycles; fatigue was subsequently conducted following the same methodology on the distal marginal ridge (Fig. 3 E and F). This sequence of loading was sequentially altered after every five samples to initiate on the distal ridge and then on the mesial to minimize bias. Every 125,000 cycles the fatigue test was interrupted for crowns and ceramic indenter surface damage inspection under a stereomicroscope (Leica Zeiss MZE, Mannheim, Germany) illuminated by an external light source (Leica CLS 150D, Mannheim, Germany). The specimens and indenters were repositioned and checked by double-sided occlusal marking film for fatigue of additional 125,000 cycles until next inspection. The second location of fatigue testing in a sample, which occurred at the opposite marginal ridge, was only performed when damage (fracture or detectable cracks) was confined to the first fatigued marginal ridge.

Porcelain cohesive fracture or delamination of veneering ceramic, or core bulk fracture were used as criteria for failure, whereas the marginal ridges that presented only cracks or quasi-plastic mode were deemed suspended after  $10^6$  cycles. After mechanical testing, the marginal ridges classified as fail-



**Fig. 2 – Programat® EP 3000—firing and glaze protocols for e.Max Ceram and IPS d.SIGN porcelains fused to zirconia and metalceramic framework, respectively. Glaze program table follows the manufacturer recommendations which indicate a slow cooling protocol for e.Max Ceram (PFZ) and a rapid cooling protocol for IPS d.SIGN (MC).**

ure were inspected at the scanning electron microscope (SEM) and the suspended samples were embedded in epoxy resin (Resina Epoxica RD6921, Rederelease, São Paulo, Brazil), and serially polished along crack extension with increasingly finer grit silicon carbide papers (100, 240, 320, 400, 500, 600 grits), under copious water irrigation, followed by 6 and 3 µm diamond pastes (Arotec, São Paulo, Brazil) applied on wet cloths. Subsurface damage was inspected by means of a stereomicroscope (Leica Zeiss MZE, Mannheim, Germany).

In an attempt to determine if there was any difference between cycling on the mesial and distal marginal ridge in the same crown the Kruskal-Wallis and Wilcoxon matched pair test with an  $\alpha$  set to 0.05 significance level was performed. The number of cycles for failure during fatigue were recorded for Weibull analysis (Synthesis 9, Weibull 9++; Reliasoft, Tuc-

**Table 1 – Weibull modulus and number of cycles when 62.3% of the specimens would fail.**

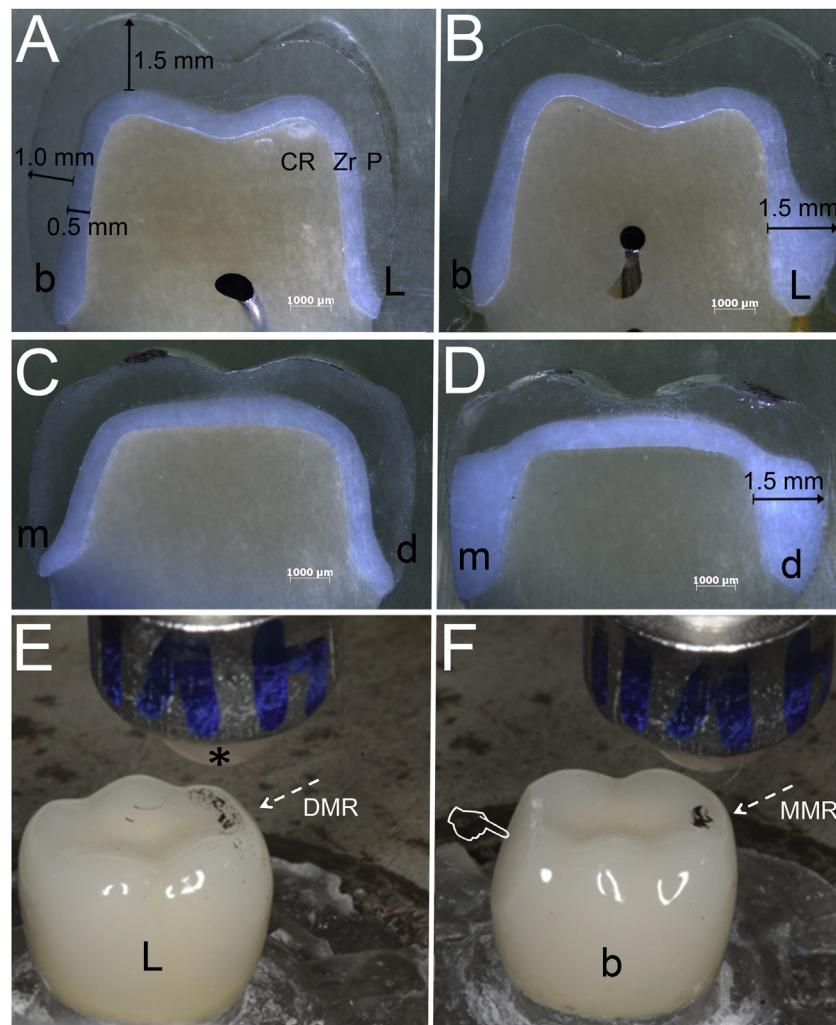
Groups	Weibull modulus ( $m$ )	Cycles (n)
MCev	1.64	374,850
MCm	1.11	367,440
PFZev	0.40	992,570
PFZm	0.68	580,150

son, AZ, USA). A probability Weibull plot was used to illustrate data distribution as a function of elapsed cycles. For fatigue life differences between groups, a contour plot was created using Weibull modulus ( $m$ ) vs. characteristic value Eta (cycles) (90% 2-sided confidence bounds). Non-overlap of contour plots indicates a significant difference between groups. Finally, the probability of survival at accumulated fatigue intervals used for sample inspection (every 125,000 cycles) was calculated and also presented in a plot. Reliability predictions beyond 1 million cycles were made only for groups with a probability of survival  $\geq 10\%$  at the end of tests.

### 3. Results

The probability Weibull plot shows a narrower scatter in data for metal ceramic groups (failures occurring in a more homogeneous range of cycles) relative to PFZ resulting in a more steep confidence line for the former (Fig. 4a). The contour plot, presented in Fig. 4b depicts the number of cycles vs. Weibull modulus (which indicates the amount of cycles at which 63.2% of the specimens of each group would fail) for group comparison (Table 1). Note that, although the PFZev group showed the broadest cycle distribution, its contour overlapped with that of the PFZm group and therefore were not statistically different. MCev and MCm groups also overlapped but only the latter overlapped with PFZm. For this reason, a detailed probability of survival characterization was made to detect the cycle interval where differences between groups started to occur (Table 2). A significant decrease in probability of survival between groups started to occur at 625,000 cycles, and it was observed only for MCev (9.84%) compared to PFZev (43.69%). At 750,000, 875,000, and 1 million cycle intervals, MCev presented a significantly lower probability of survival compared to both PFZ groups, whereas MCm presented intermediate values. Since survival probability was less than 10% at 1 million cycles for both metal ceramic groups, predictions at 1.5 and 2 million cycles were only made for porcelain fused to zirconia crowns, which presented a non-significant decrease neither as a function of cycles nor of framework design (confidence bound overlap). The reliability plot (Fig. 4c) depicts the data shown in Table 2 where the probability of survival sequentially decreases for groups PFZev, PFZm, MCm, and MCev, respectively.

The PFZ groups presented marginal ridge fractures ( $n=13$  from the PFZev and  $n=15$  from the PFZm), but more suspensions compared to metal ceramic crowns and were thus polished for near field damage characterization (Fig. 5A-D). All marginal ridges of the metal ceramic crowns failed before completion of  $10^6$  cycles, except for a marginal ridge from MCm group which was considered suspended (Fig. 5E and F). The number of matched pairs included in the statistical infer-



**Fig. 3 – Micrographs showing the dimensions of the core and veneering porcelain in a bucco-lingual section of a PFZ sample with (A) even thickness and (B) modified framework where the main difference is the presence of the lingual collar. Images C and D are proximal sections of PFZ crowns with even thickness and modified framework designs, respectively, where the proximal strut's dimension is shown. To standardize indenter contact location, articulating paper was used and load was delivered at the distal marginal ridge (DMR, dotted arrow) (E) until fracture (pointer) (F) which in this scenario, due to fracture extension, allowed the embedded crown assembly to be rotated and the mesial marginal ridge (MMR) fatigued.**

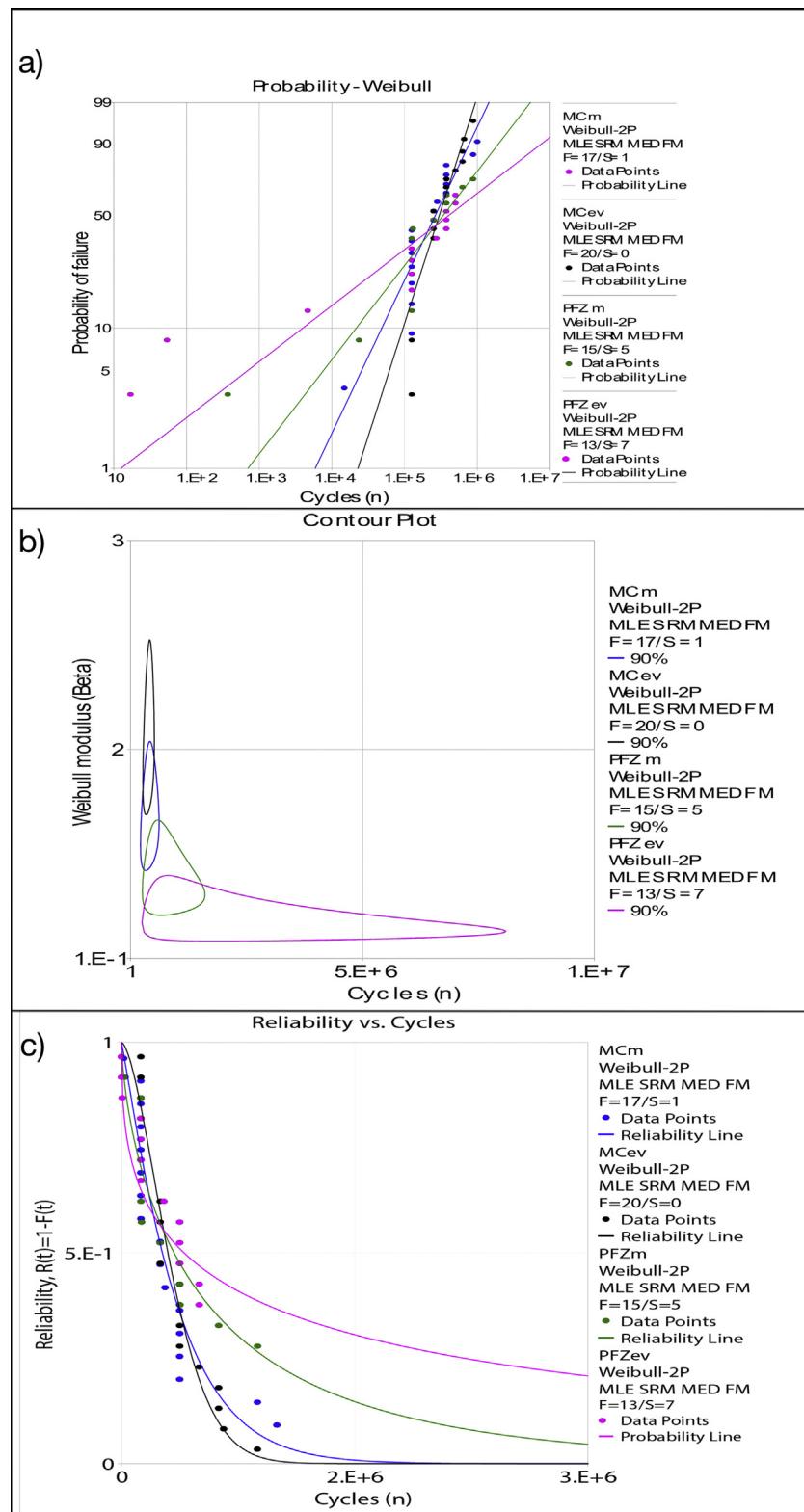
ences was  $n=20$  for all groups with the exception of group MCm, which resulted in 18 tested ridges since two crowns presented fracture extension that hindered testing on the second marginal ridge. Kruskal-Wallis and Wilcoxon matched pair tests depicted that marginal ridge location (mesial or distal) did not significantly affect fatigue life ( $p < 0.05$ ).

### 3.1. Failure modes

Porcelain veneer fracture was observed in all marginal ridges of MCev group, in 17 of 18 ridges of the MCm group (Fig. 6), in 13 marginal ridges of the PFZev group (Fig. 7), and in 15 from the PFZm group. Two crowns of the MCm group presented extensive porcelain fractures in the first loaded ridges which hindered further testing at the other proximal ridge. In general, the extension of the porcelain veneer fractures, often leading to delamination, was more pronounced in the MCev

compared to the MCm group. Such a difference in porcelain veneer fracture size was not observed between PFZ in spite of the framework design. Qualitative fractography performed in polarized-light microscopy and SEM showed the presence of quasiplastic deformation at the indentation area which became evident upon the first inspection (125,000 cycles). Telltale fractographic marks including hackles, wake hackles, arrest lines, and twist hackles suggesting the direction of crack propagation from the indentation area were identified in both MC and PFZ groups.

The suspended crown in the MCm group, which was sectioned for inspection in the polarized light microscope, presented inner cone crack confined in the porcelain veneer that initiated at the occlusal surface and extended to the proximal area not reaching the core/veneer interface (Fig. 5E and F). In contrast, of the 7 suspended PFZev marginal ridges, 5 presented inner cone cracks extending to the porcelain/veneer



**Fig. 4 – (a) Probability Weibull plot showing the probability line for MCm, MCev, PFZm and PFZev and the data scatter as a function of cycles. (b) Contour plot (Weibull modulus vs. cycles for group comparisons) shows the absence of statistical difference where contour plots overlap. (c) Probability of survival as a function of cycles depict an overlapped lifetime between groups until roughly 1 million cycles and from then on an increased lifetime for porcelain fused to zirconia crowns.**

**Table 2 – Probability of survival calculation at every 125,000 until 1 million cycles. Note that differences between groups started to occur from 625,000 cycles on (non-overlap between upper and lower limits). Calculation at 1.5 and 2 million cycles were only made for porcelain fused to zirconia crowns (not significant for modified or even thickness framework designs) since probability of survival calculations for metal ceramic groups were negative at both time points.**

Cycles	Probability of survival %							
	MC – E	Upper Lower	MC – ALT	Upper Lower	Zr – E	Upper Lower	Zr – ALT	Upper Lower
125,000	84.86	92.44	74.02	85.1	65.1	77.48	70.5	81.96
		70.97		57.07		48.57		54.11
250,000	59.84	72.9	52.15	66.46	56.57	70.15	57.02	70.33
		43.41		35.43		40.04		40.79
375,000	36.76	50.78	35.95	50.78	51.06	65.42	47.63	61.87
		22.82		21.35		34.48		31.8
500,000	20.06	32.89	24.43	38.84	46.96	61.94	40.53	55.41
		9.82		12.24		30.33		25.11
625,000	9.84	20.59	16.41	29.98	43.69	59.2	34.91	50.3
		3.33		6.65		27.04		19.96
750,000	4.37	12.66	10.92	23.39	40.99	56.95	30.35	46.14
		0.87		3.42		24.34		15.92
875,000	1.77	7.69	7.21	18.43	38.68	55.05	26.58	42.66
		0.18		1.68		22.06		12.74
1,000,000	0.66	4.63	4.73	14.64	36.68	53.4	23.41	39.7
		0.03		0.79		20.11		10.21
1,500,000		31	48	15	31			
			14		4			
2,000,000		26	45	10	26			
			11		2			

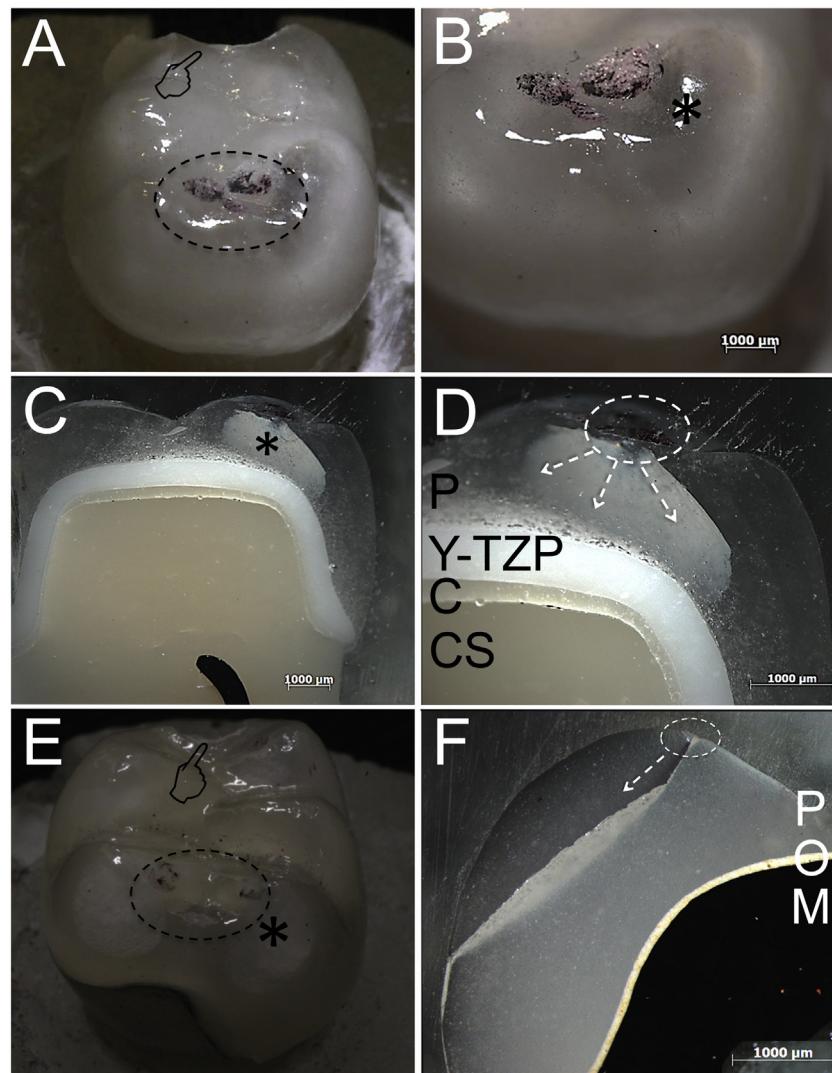
interface (Fig. 5A–D) one was confined within the porcelain veneer, and one presented damage restricted to the quasiplasticity zone. PFZm suspended crowns showed less inner cone cracking reaching the core/veneer interface ( $n=1$ ) whereas the remaining 3 were confined within the porcelain veneer and one depicted damage limited to the quasiplasticity zone.

#### 4. Discussion

The postulated null hypothesis that fatigue life would not be improved by framework design modification was accepted. Since PFZ led to an increase in probability of survival compared to MC crowns, the second hypothesis that material used to fabricate crowns would not improve fatigue life was rejected. Both results are generally in contrast with previous literature. Alterations in crown framework design aiming to improve support have commonly resulted in improvements reported in *in vitro* [22,47], as well as in clinical studies [48,49]. Similarly, compilation of data from a plethora of clinical studies reported in systematic reviews have shown that the incidence of porcelain cohesive fractures in zirconia crowns [50] and fixed dental prostheses [51] are significantly higher than observed in metal ceramic reconstructions. However, it is important to acknowledge that both systematic reviews [50,51], comprised clinical studies published until 2013 which generally predate the currently proposed changes in the laboratory processing of zirconia veneered reconstructions, including slow cooling protocols, shown to substantially improve outcomes [26,52].

The design modification suggested in the present manuscript are based on empirical guidelines suggested decades ago for metal ceramics [53] and later applied to PFZ reconstructions due to porcelain fractures occurring in a higher prevalence than expected [54]. Another design, namely anatomical, which involves the use of a coping that is similar to the final crown anatomy, assuring an even and reduced thickness of the veneering material, has similarly shown reduced fracture sizes but whereas a selective improvement in probability of survival was observed only for pressed onto anatomical, a substantial decrease in this parameter was found for pressed onto even thickness frameworks [47]. Therefore, improvements in reliability cannot be explained only by framework design modifications, since in the same study porcelain veneered onto either even thickness or modified framework designs presented similar reliability, and both as high as that observed for porcelain pressed onto anatomical copings [47].

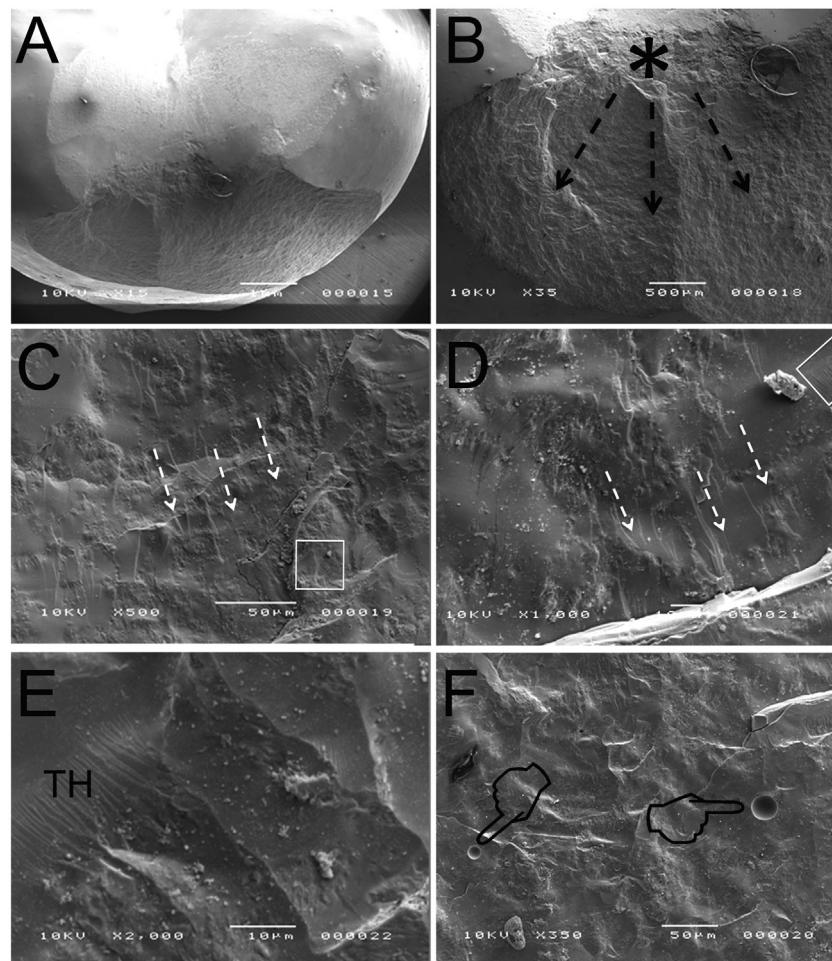
The benefits of the core design modification evaluated herein are also controversial in the literature due to the overall differences in fatigue methodology and location of indenter contact during testing [21,27,55]. When fatigue was delivered at the occlusal fossa, PFZ crowns fabricated through a customized slow cooling protocol showed a significant increase in fatigue life compared to rapid cooled crowns, regardless of framework design, suggesting that the advantages of the lingual collar and proximal struts are questionable [26]. Whereas the latter study was performed only in PFZ crowns and with the same method and equipment used in the present study,



**Fig. 5 – Representative micrographs of suspended crowns from both PFZ and MC groups.** (A) The porcelain fracture extension on the distal marginal ridge of a PFZev crown most commonly remained confined to the proximal area (pointer), allowing fatigue testing of the opposite mesial ridge. In this sample, the mesial ridge was suspended since it endured the 1 million cycles mission. (B) A magnified view of the indented area (circle) depicted in A shows through translucency the subsurface crack propagation which was further characterized during epoxy resin embedding and sectioning (asterisk) (C). Light-polarized micrograph shows inner cone crack (asterisk) magnified in (D) depicting its origin immediately below the quasiplastic zone and extending towards the zirconia framework (arrows). P = Porcelain fused to zirconia, Y-TZP = Y-TZP framework, C = cement line, CS = composite substrate. (E) Crown of the McM showing a porcelain cohesive fracture confined to the mesial marginal ridge (pointer) which allowed testing of the distal ridge. It was the only suspended crown of this group and it showed a inner cone crack initiating at the indentation area (circle shown in E) and propagating towards the proximal areas without leading to final fracture (asterisk). (F) After polishing, the inner cone crack is depicted with its origin at the indentation contact (circle) and propagation towards the proximal (arrow) not reaching the framework. P = Porcelain fused to metal, O = opaque, M = Metalceramic framework.

the major difference was the load application on the marginal ridges instead of at the center of the occlusal fossa. However one clinical aspect that remains commonplace in framework design modifications and that fosters its indication is the decreased fracture extension when compared to even thickness core designs, which may facilitate chairside repair if porcelain fracture occurs [21,22,26,27,47,56].

Whereas no significant differences were observed between groups as a function of core design modifications, which is both in line [26,47] and also contrasting to previous literature [22], most intriguing was the inferior results observed for metal ceramic compared to PFZ which contrast most of the published information thus far [50,56]. Potential explanations include previous evaluations of the residual stress profile in veneering ceramics of PFZ and MC samples show-

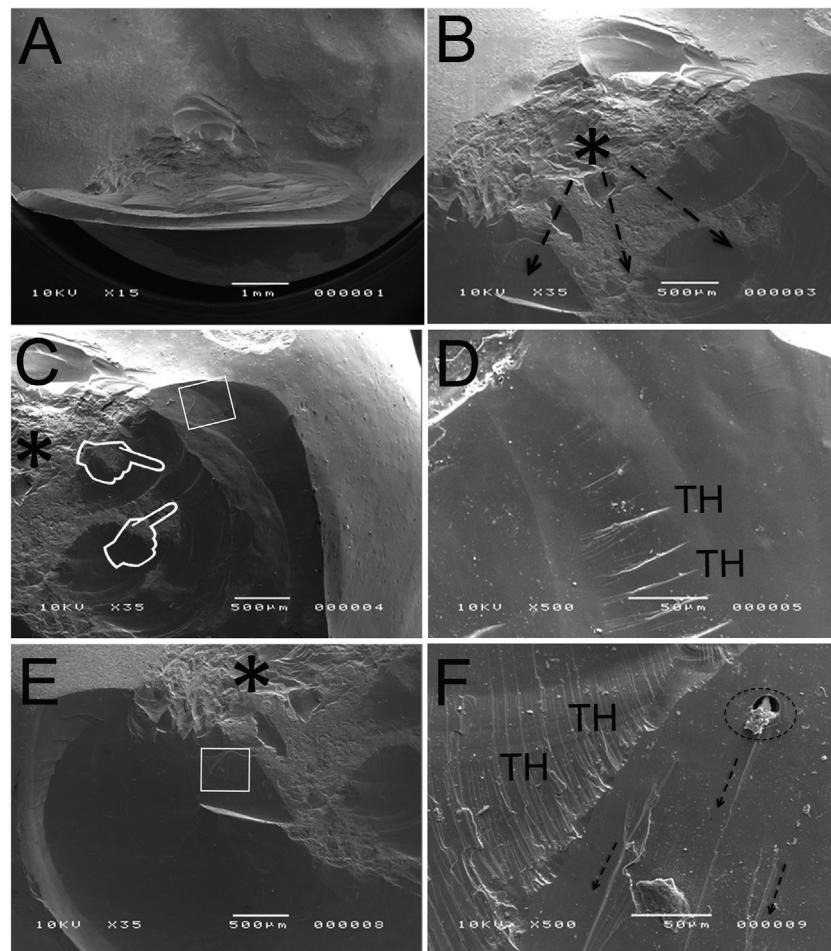


**Fig. 6 – Representative scanning electron micrographs of a marginal ridge failure in the MCm group.** (A) An occlusal and (B) proximal views depicting the indentation area presenting quasiplastic deformation (asterisk), involving only the marginal ridge of crown. The arrows point the direction of crack propagation. (C) The fracture origin was associated to the occlusal indentation area corroborated in this micrograph by several hackles pointing towards the cervical margins (arrows). (D) Immediately below the arrows shown in (C), a magnified view depicts more hackles and marks such as (E) twist hatches (TH) which indicate crack direction and the possible presence of residual stress. (F) Voids were often observed in the porcelain veneer of MC crowns (pointers).

ing that stresses in PFZ are compressive and start to become tensile around 0.9 mm from the surface, whereas in MC compressive stresses start to decrease from the surface already at 0.5 mm until 1 mm [57]. Although residual stresses were not evaluated in the present study, it is likely that fatigue loading and the resulting near surface damage (water-assisted inner cone cracks depicted in our sectioned samples) was equally confined to subsurface compressive stresses for both groups until 625,000 cycles, when differences between core materials were first detected. As cycles elapsed from this point on and water-assisted inner cone cracks continued to propagate, cracks likely entered an increased area of decreased compressive and/or tensile stresses for MC compared to PFZ, which eventually lead to a reduction in probability of survival for MC.

Besides manufacturing process (i.e., porosities and microstructural defects) [58], slow cooling to reduce residual stress within the porcelain veneer of PFZ reconstructions [25,26,52,59–61] and coefficient of thermal expansion mis-

match [62,63], recent clinical evidence has shown a major influence of occlusal contact location on the incidence of all-ceramic reconstructions failure [8,29]. In natural occlusion, contacts typically involve marginal ridges [13,14,64–67] and are sometimes exclusive of this occlusal surface area [13,14]. Remarkably, the broadest fractographic study published thus far of alumina and zirconia veneered restorations in service up to 9 years has systematically showed the majority of fractures initiating at mesial or distal ridges and concluded that such contacts should be eliminated [8]. In addition, it was suggested that occlusal contact on unsupported ceramic should be avoided, although the ideal amount of support for the veneering porcelain remains undefined. From such a perspective, our study attempted to simulate a worst case scenario while loading directly on the marginal ridges, and also tested the concept of core design modification which is theoretically supposed to improve ceramic support at the proximal areas.



**Fig. 7 – Representative scanning electron micrograph of a porcelain cohesive fracture limited to the marginal ridge of a PFZev crown. (A) Occlusal and (B) proximal views show the indentation area (asterisk), and the direction of crack propagation (arrows). (C) Several arrest lines are present with their concave portion pointing towards the fracture origin (pointer) at the indentation area. (D) The margin limited by the square shown in (C), depicts a series of twist hackles (TH) confirming crack propagation towards the margins of the fractured surface. (E) Overall view of the opposed fractured margin shows the damage at the indenter leading to the formation of a quasiplastic zone. Immediately below this area (square) and magnified in (F) the presence of twist hackles and a wake hackle (dotted circle) which as a hackle extending from the void at the crack front towards crackling is depicted.**

Clinically, fractures involving proximal contacts hinder repair and require restoration replacement.

The lithium disilicate indenter was chosen due to its modulus of elasticity (95 GPa) and wear being similar to enamel (94 GPa) [68,69]. Quasiplastic deformation at the indentation area was observed in all specimens after the first 125,000 round of cycles. The analysis performed every 125,000 cycles, revealed near-field damage (outer/inner cone cracks) originating immediately below the indentation area, as previously reported [21,22,26,27,47,56,68–71], whereas radial cracking was not observed corroborating its rare finding in Y-TZP cores.

## 5. Conclusion

In the limitations of the present study the postulated null hypothesis, which stated that different framework designs

would not improve the fatigue life of metal-ceramic and Y-TZP, was accepted. However, significant difference was found when different systems were compared, where the PFZev group presented increased fatigue life compared to metal-ceramic groups.

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