Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/dema

Lifetime prediction of veneered versus monolithic lithium disilicate crowns loaded on marginal ridges

Vitor Guarçoni de Paula[a], Gerson Bonfante[a], Fabio C. Lorenzoni[b], Paulo G. Coelho[c,d,e], Leonardo Rigoldi Bonjardim[f], Vinicius P. Fardin[g], Estevam A. Bonfante[a,*]

[a] Department of Prosthodontics and Periodontology, University of São Paulo, Bauru School of Dentistry, Bauru, SP, Brazil
[b] Department of Prosthodontics, Unigran University School of Dentistry, Dourados, MS, Brazil
[c] Department of Biomaterials and Biomimetics, New York University, New York, NY, USA
[d] Hansjörg Wyss Department of Plastic Surgery, NYU Langone Medical Center, New York, NY, USA
[e] Mechanical and Aerospace Engineering, NYU Tandon School of Engineering, New York, NY, USA
[f] Department of Biological Sciences, University of São Paulo, Bauru School of Dentistry, Bauru, SP, Brazil
[g] Department of Prosthodontics, Universidade Vila Velha, Vila Velha, ES, Brazil

ARTICLE INFO

Article history:
Received 4 September 2018
Received in revised form
2 December 2018
Accepted 11 January 2019

Keywords:
Fatigue
Porcelain
Lithium disilicate
Crowns

ABSTRACT

Objective. To evaluate the probability of survival of monolithic and porcelain veneered lithium disilicate crowns comprised by a conventional or modified core when loaded on marginal ridges.

Methods. Lithium disilicate molar crowns (n = 30) were fabricated to be tested at mesial and distal marginal ridges and were divided as follows: (1) bilayered crowns with even-thickness 0.5 mm framework (Bi-EV); (2) bilayered crowns with modified core design (Bi-M-lingual collar connected to proximal struts), and: (3) monolithic crowns (MON). After adhesively cemented onto composite-resin prepared replicas, mesial and distal marginal ridges of each crown (n = 20) were individually cyclic loaded in water (30–300 N) with a ceramic indenter at 2 Hz until fracture. The 2-parameter Weibull was used to calculate the probability of survival (reliability) (90% 2-sided confidence bounds) at 1, 2, and 3 million cycles and mean life.

Results. The reliability at 1 and 2 million cycles was significantly higher for MON (47% and 19%) compared to Bi-EV (20% and 4%) and Bi-M (17% and 2%). No statistical difference was found between bilayered groups. Only the MON group presented crown survival (7%) at 3 million cycles. The mean life was highest for MON (1.73E + 06), lowest for Bi-M (573,384) and intermediate for Bi-E (619,774). Fractographic analysis showed that the fracture originated at the occlusal surface. The highest reliability was found for MON crowns. The modified framework design did not improve the fatigue life of crowns.

Significance. Monolithic lithium disilicate crowns presented higher probability of survival and mean life than bilayered crowns with modified framework design when loaded at marginal ridges.

* *Corresponding author at*: Alameda Otávio Pinheiro Brisola 9-75, Bauru, SP, 17.012-901, Department of Prosthodontics and Periodontology, University of São Paulo, Bauru School of Dentistry, Brazil.
E-mail address: estevam.bonfante@fob.usp.br (E.A. Bonfante).

https://doi.org/10.1016/j.dental.2019.01.007
0109-5641/

1. Introduction

Lithium disilicate (LDS) has been widely used due to its versatility, strength and high esthetic properties allowing its indication as thin veneers, inlays, onlays, bilayered or monolithic crowns, anterior and posterior 3-unit fixed dental prostheses [1]. When used as lithium disilicate bi-layered single crowns, a long-term prospective study showed that the rate of complication-free crowns was 95.3% after 5 years and 82.9% after 8 years [2]. The use of lithium disilicate as monolithic crowns seems to be more promising due to the absence of porcelain veneer fractures as reported in a recent 5-year clinical trial showing 100% survival [3]. Since the indication of monolithic or bi-layered use will vary according to the degree of discoloration of abutment teeth [4], the potential improvement in performance of bi-layered LDS through framework design modification, as previously observed for porcelain-fused to zirconia restorations in laboratory [5] and clinical trials [6,7], warrants investigation.

When the crown is fabricated using two different materials for core and porcelain veneer, the strength of the crown can significantly decrease when compared to monolithic crowns [8–10]. The reasons are possibly related to: the lower fracture toughness of porcelain veneer compared to the core material [11,12], the reduction of core thickness to allow thicker porcelain veneer which could decrease the mechanical properties [13], the conventional manual layering technique that could incorporate flaws located at the porcelain veneer or at the core–porcelain veneer interface [14], and the resulting multilayer structure which could increase the complexity of stress distribution within bilayered restorations [11,12,15]. A previous short-term (2-year) prospective clinical study evaluated monolithic lithium disilicate and no mechanical failures such as fracture or chipping were observed [16,17].

Porcelain veneer fractures are multifactorial where main subcritical crack growth mechanisms such as cyclic fatigue and stress corrosion predominate [18,19]. Clinical evaluations have suggested that porcelain fracture is frequently associated with occlusal wear and areas without porcelain support such as marginal ridges [7,20–24]. Although empirically suggested in the past that porcelain veneer should have an even thickness, of no more than 2 mm, and be supported by the core [25], some clinical trials have reported that core design modifications may decrease chipping rates [6,7,26]. When the prostheses framework is modified to improve porcelain support, some in vitro studies [13,27–31] have shown that fracture extension is reduced, potentially allowing chairside repair. Most of these studies have been conducted in bilayered zirconia crowns where framework fracture is a rare event [32], in contrast to veneered glass-ceramic restorations [33].

The location of occlusal contacts on porcelain veneered crowns seems to negatively influence restorations performance [24]. Typically, occlusal contacts occur between cusps and occlusal fossa or marginal ridges [34,35]. The marginal ridge of prosthetic crowns may present the largest bulk of ceramic material unsupported by the framework [28,29,31]. Finite element analysis have shown high tensile stress located at marginal ridges and proximal areas specially in molars [36] and second premolars [37,38]. Consequently, several clinical studies have reported fractures in proximal areas of all-ceramic crowns [20,21,23,24,39–48] which commonly demand restoration replacement and additional costs [24].

Although loading on marginal ridges seems to be critical because framework support is commonly not ideal for porcelain at this location, a previous study showed that fatigue life of zirconia-veneered was improved compared to metal-ceramic crowns regardless of framework design [31]. Since lithium disilicate presents lower fracture toughness than zirconia, its survival when used as framework for porcelain veneering or as monolithic crowns subjected to loading at marginal ridges is unknown. Therefore, the present study sought to evaluate the fatigue life and failure modes of monolithic and bilayered lithium disilicate crowns with conventional and modified framework designs. The following hypothesys tested was that fatigue life would be highest for monolithic lithium disilicate crowns, followed by porcelain veneered onto crowns with framework design modification.

2. Materials and methods

2.1. *Sample preparation*

An artificial mandibular first molar positioned in a mannequin (Plastic mannequin tooth – MOM, Marilia, SP, Brazil) was prepared to receive a full crown by reducing the axial walls by 1.5 mm, the occlusal surface by 2.0 mm and shoulder margin (1.2 mm of thickness) with rounded internal angles. Subsequently, 30 composite resin prepared tooth replicas were obtained by vinyl polysiloxane impression (Express – 3M Oral Care, St. Paul, MN, USA), which was incrementally packed with composite resin (Z100 – 3M Oral Care, St. Paul, MN, USA) and light-cured (Ultralux, Dabi Atlante, Ribeirão Preto, SP, Brazil) according to manufacturer's instructions. All replicas were stored in distilled water for at least 30 days to minimize dimensional alterations [49]. Each replica was vertically positioned in 25 mm diameter PVC tubes guided by polyvinyl siloxane matrix (Express – 3M Oral Care) during the embedding process of acrylic resin (Jet, Clássico Artigos Odontológicos, São Paulo, SP, Brazil). The preparation finish line was maintained 2 mm above the potting surface. Stone dies were acquired from polyether impressions (Impregum F – 3M-Oral Care, St. Paul, MN, USA) of each resin-tooth replica and randomly divided in 3 groups (n = 10 each) as follows: 1) bilayered crowns with even-thickness frameworks (Bi-EV); 2) bilayered crowns with modified framework design (Bi-M: lingual collar connected to proximal struts), and: 3) monolithic crowns (MON). For sample size calculation, Simumatic tool (Weibull++, Synthesis 9, Reliasoft, Tucson, USA) was used to generate a data set for a 2-parameter Weibull distribution (90% confidence intervals) with assumed beta values of 0.5, 1, and 1.5 and eta of 1 million cycles for sample sizes of 10, 20, 50, and 100 [50–52]. Considering the shape parameter beta approximate to 1, found in the initial set of results and a previous investigation [31] and the further calculation of average relative biases (ARB, difference between assumed and resulting betas) the ARB remained

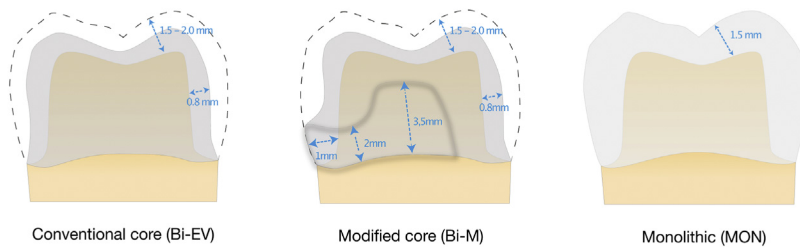

Fig. 1 – Schematic proximal view of even-thickness, modified core designs, and monolithic crown, from left to right, respectively. The modified core presented the same configuration of the conventional even-thickness core at the buccal surface, but it had proximal struts (mesial and distal surfaces) of approximately 3.5 mm height which were connected by a lingual collar of 2 mm height and 1 mm thickness. Dashed line indicates the veneering porcelain.

below 10% (1%, 9%, 3%, and 1% for sample sizes of 10, 20, 50, and 100, respectively).

Lithium disilicate cores were fabricated using the lost wax casting technique. The Bi-EV group presented a 0.8 mm even thickness coping and the Bi-M group presented a 0.8 mm even thickness coping with a 1 mm thick lingual collar (2.0 mm of height), connected to proximal struts (3.5 mm of height, Fig. 1). The monolithic full anatomical crowns (MON) were waxed to their final occlusal anatomy, with occlusal thickness of 1.5 mm (Fig. 1), following the manufacturer's minimum thickness recommendations for the molar region [53]. The wax cores and crowns were invested (Speed Vest, Ivoclar Vivadent, Liechtenstein), subsequently the heating allowed the wax removal followed by filling with pressable material (IPS e.max Press, HT B1, Ivoclar Vivadent, Liechtenstein). After the heat pressing procedure, the cores and monolithic crowns were divested and sandblasted with 120 μm glass beads at a pressure of 2 bar.

The monolithic crowns were glazed (IPS e.max Ceram Glaze Paste, Ivoclar Vivadent, Liechtenstein) and fired at 725 °C, whereas the conventional and modified design cores were veneered with low-fusing dental porcelain (IPS e.max Ceram Transpa Clear, Ivoclar Vivadent, Liechtenstein) using hand-layering process following the manufacturer recommendation (Programat EP 3000, Ivoclar Vivadent, Liechtenstein) [53]. Subsequently, the crowns were manually finished and polished before the glaze firing. A silicone matrix (Zetalabor – Zhermack, Badia Polesine, Rovigo, Italy) of the occlusal surface of a mannequin molar tooth was used to guide and standardize the porcelain veneer contour. The occlusal and axial surfaces, including the core and porcelain veneer, presented approximately 2.0 and 1.5 mm of thickness, respectively. The glaze layer (Glaze Paste and Stain Liquid Long Life, IPS e.Max Ceram – Ivoclar Vivadent AG, Schaan, Liechtenstein) was applied onto the porcelain surface and treated according to manufacturer's instruction [53].

The inner surfaces of all glazed crowns were etched with 10% hydrofluoric acid (Dentsply Porcelain Conditioner, Dentsply, USA) for 20 s and silanized (Rely X Ceramic Primer, 3 M Oral Care, St. Paul, MN, USA) for 60 s. The crowns were cemented on the aged composite resin replicas of a molar using a self-adhesive resin cement (Rely X U200, 3 M Oral Care) under a 50 N static occlusal load for 10 min. The luting agent was light-cured from five directions (Ultralux, Dabi Atlante, Ribeirão Preto, SP, Brazil). Finally, all specimens were stored in distilled water at 37 °C for 24 h prior to testing.

2.2. *Fatigue test*

Fatigue test was carried out in a fatigue machine (Model MSFM – Elquip – São Carlos, SP, Brazil) in r-ratio mode at a 30–300 N load range, under distilled water (37 °C) at 2 Hz until failure [28,29,31]. As the indenter was in contact with the specimen, the initial contact load of 30 N was applied without abrasion, attrition or impact, steadily increasing to 300 N and decreasing back to 30 N. The load was applied through a spherical monolithic lithium disilicate indenter (3.18 mm radius) on the marginal ridges, (mesial and distal) of each group (n = 20).

The lithium disilicate indenter was fabricated through waxing poured in a custom metal spheric device. Sixty ceramic indenters were fabricated so each marginal ridge was cycled with a new indenter. The lithium disilicate glass-ceramic was chosen due to its elastic modulus ([E] = 95 GPa) and wear patterns similar to dental enamel. ([E] = 94 GPa) [1,31,41,54].

The goal of the study was to simulate a common occlusal relationship in natural dentition where one cusp occludes against one or two marginal ridges [34–37,55–59] Every 125,000 cycles, the fatigue test was interrupted for crown surface damage inspection under stereomicroscopy (Leica Zeiss MZE, Mannheim, Germany). Subsequently, the specimens were repositioned in the machine for an additional 125,000 cycles or until failure.

Initially, the mesial marginal ridges were fatigued until fracture and if these fractures did not extend the mesial marginal ridge, the distal marginal ridges were fatigued. In the subsequent crown, fatigue started at the distal marginal ridges and this alternation of ridge location was subsequently maintained throughout the experiment.

2.3. *Failure mode characterization*

The criteria for failure were chipping, delamination or catastrophic fractures in monolithic or bilayered crowns. Representative fractured surfaces were characterized under polarized-light microscopy (MZ- APO stereomicroscope, Carl Zeiss MicroImaging, Thornwood, NY, USA) followed by Scanning Electron Microscopy (SEM) (Model S-3500N; Hitachi, Japan). Fractographic analysis for characterization and determination of the origin of the fractures according to the methodology described by Quinn (2007) [60] were performed.

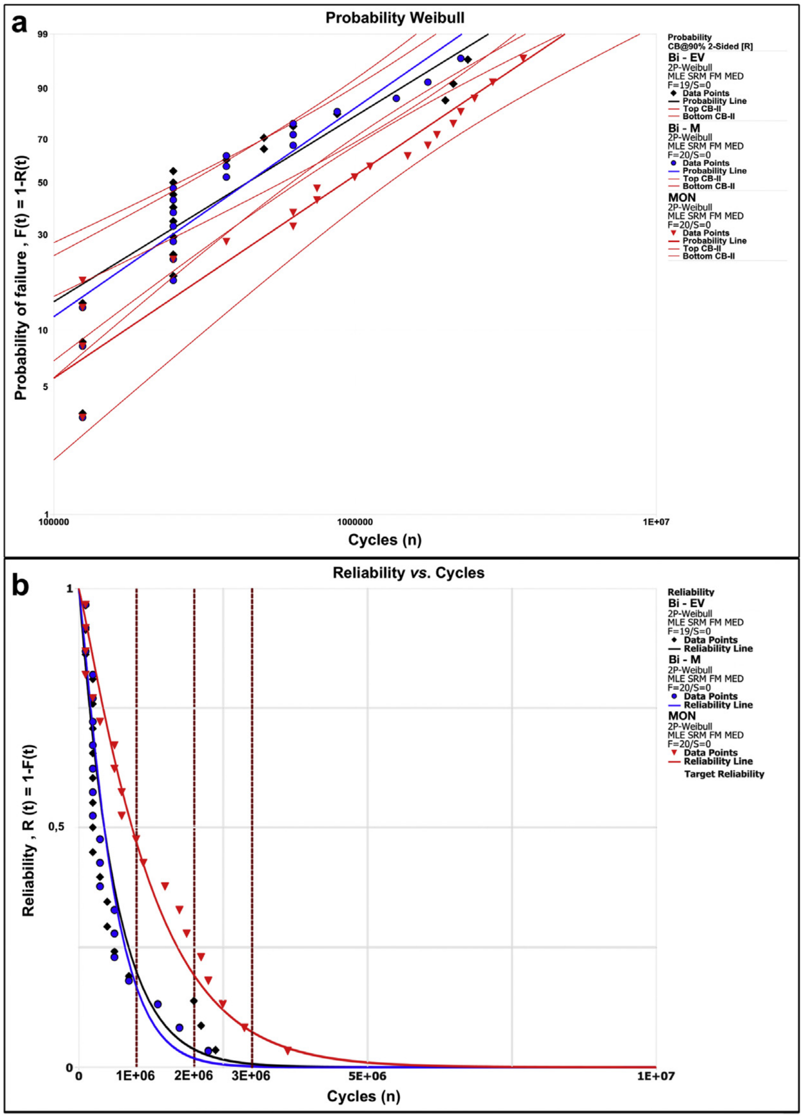

Fig. 2 – (a) Probability Weibull 2P plot with 90% of confidence interval and (b) Reliability plot showing probability lines of bilayered crowns and monolithic fully anatomy crowns vs. number of cycles. The vertical dashed lines in (b) indicate the cycling times of 1, 2 and 3 million, from left to right, respectively.

2.4. *Data analysis*

In order to check if there was any difference in the number of cycles required for fracture between the marginal ridges a paired t test with significance level of 5% ($p < 0.05$) (6 Prism, GraphPad Software, La Jolla, CA USA) was performed for each group individually.

The failure during fatigue was recorded as a function of cycles. This information was used to determine the survival probability (reliability) by Weibull 2 parameter distribution fit for each group (Synthesis 9, Weibull ++; Reliasoft, Tucson, AZ, USA). Weibull modulus (*m*) and characteristic strength Eta (n) (here the number of stress cycles (n) at which 62.3% of the specimens would fail) were determined for each group.

The survival or failure information collected during cycling (every 125,000 cycles) was used to calculate the reliability of each group at 1, 2 and 3 million cycles and also to calculate their mean life (Quick Calculation Pad, Synthesis 9, Weibull ++ Reliasoft, Tucson, AZ, USA). These ranges were selected based on results and from the reliability graph displayed according cycles revealed that this interval was relevant as a function of the failure distribution. Therefore, to check for statistically significant differences between groups at 1, 2 and 3 million cycles the presence or absence of overlap between the upper and lower limits confidence intervals (90% bilateral) was observed.

3. Results

3.1. *Fatigue test*

The paired t-test used to compare the mesial and distal marginal ridges within groups did not show normal disper-

Table 1 – Weibull modulus (m) and characteristic strength (express the number of cycles in which 62.3% of the specimens would fail).

Groups	Weibull modulus (m) (upper-lower confidence intervals)	Eta-cycles (n) (upper-lower confidence intervals)
Bi - EV	1.02 (0.78–1.35)	626,785 (423,981–926,596)
Bi - M	1.15 (0.89–1.51)	603,354 (430,085–846,430)
MON	1.12 (0.83–1.51)	1.368.564 (1.00E + 06–1.87E + 06)

sion of results for Bi-M group. Thus, the Wilcoxon test was used to depict that mesial or distal marginal ridges did not affect fatigue life. The comparison showed that no statistic significant difference ($p > 0.05$) was found. Thus, as the marginal ridges presented similar occlusal surface, the amount of 20 specimens was accounted for each group, except for one crown in the Bi-EV group that presented one major fracture extending to the mesial marginal ridge (n = 19).

The Bi-EV and Bi-M crowns had most of the fractures occurring before 1 million cycles (Bi-EV n = 16 and Bi-M n = 17), except for six marginal ridges (n = 3 from each group) that survived 1 million cycles, and n = 3 failed after 2 million (Bi-EV n = 2 and Bi-M n = 1). During fatigue testing, half (n = 10) of the marginal ridges cycled of MON group survived 1 million cycles and n = 5 of these exceeded 2 million cycles.

The Probability Weibull (failure) vs. number of cycles analysis (Fig. 2a) depicts sample failure during cyclic fatigue. Bilayered crowns presented a trend in failure at the 1 million cycle range, regardless of core design (n = 16 Bi-EV and n = 17 Bi-M). The overlap between confidence bounds of Weibull probability of bilayered crowns demonstrates similar fatigue failure for these groups (Fig. 2a), whereas most monolithic crowns survived this range of cycles. Table 1 shows the values for Weibull modulus and characteristic strength of groups under fatigue.

The Reliability plot (Fig. 2b – probability of survival vs. number of cycles) showed higher number of specimens failing within 1 million cycles in bilayered groups. The MON group presented ten specimens surviving under fatigue beyond 1 million cycles. The overlap in confidence bounds between bilayered groups depicts the absence of statistical difference in reliability between these groups up to 3 million cycles, when all failed. The MON group presented comparable survival to Bi-EV at 1 and 2 million and significantly higher than Bi-M, but was the only group presenting some survival at 3 million cycles (Table 2). The calculated highest mean life was observed for monolithic crowns, the lowest for bilayered crowns with modified core design and intermediate values for even thickness core (Table 3).

3.2. *Failure modes*

Stereomicroscope analysis revealed that the origin of cracks was located at the indenter contact area. The cracks propagated at the proximal area towards buccal, lingual and cervical surfaces of the crown.

The cohesive fracture was the only type of fracture found in all groups in this study, except for the Bi-EV group that presented one framework bulk fracture exposing the prepared tooth replica. Moreover, the stereomicroscope analyses showed that the fractures presented in MON group provided minor fractures mostly restricted to the marginal ridges.

Table 2 – Reliability (90% confidence interval) of 3 the groups over as a function of fatigued cycles. Same letters indicate absence of statistical significance between groups at the same cycle range. Different uppercase letters indicate significant differences among columns in the same row.

Probability of survival (reliability) %			
Reliability %/Cycles	Bi - EV	Bi - M	MON
Upper confidence levels	33	29	61
Probability of Survival (%)-1.000.000 cycles	**20**^{a,b}	**17**^{b}	**47**^{a}
Lower confidence levels	9	7	31
Upper confidence levels	11	8	32
Probability of Survival (%)-2.000.000 cycles	**4**^{ab}	**2**^{b}	**19**^{a}
Lower confidence levels	0,6	0,2	9
Upper confidence levels	0	0	17
Probability of Survival (%)-3.000.000 cycles	**0**^{c}	**0**^{c}	**7**^{a}
Lower confidence levels	0	0	2

Table 3 – The highest mean life was observed for monolithic crowns, the lowest for bilayered crowns with modified core design and intermediate values for even thickness core. Different uppercase letters indicate significant differences between groups.

Mean life			
	Bi - EV	Bi - M	MON
upper confidence levels	917,207	808,307	1.76E + 06
MEAN LIFE	**619,774**^{a,b}	**573,384**^{b}	**1.22E + 06**^{a}
Lower confidence levels	418,793	406,738	863,243

Qualitative fractography performed in polarized-light stereomicroscope and SEM showed the presence of quasiplastic deformation at the indentation area. Telltale fractographic marks including hackles, wake hackles, twist hackles and arrest lines suggesting the direction of crack propagation from the indentation in Bi-EV and Bi-M groups (Figs. 3 and 4). The presence of voids and pores on the surface of the porcelain veneer was identified in bilayered crows. Microscopic analysis revealed a rough surface and no internal voids in the evaluated magnifications for the MON crowns. Also, the telltale fractographic marks like hackles and arrest lines identified the indentation surface as the source of the failure (Fig. 5).

The lithium disilicate indenter/crown contact caused a quasiplastic deformation pattern on both surfaces, which was observed already in the first 125,000 cycles. The SEM observation revealed that, when the surface of the indenter contacted the porcelain veneer of bilayered crowns, the deformation was more pronounced at the surface of the crown, whereas the MON crowns presented similar deformation compared to the surface of the indenter (Fig. 6).

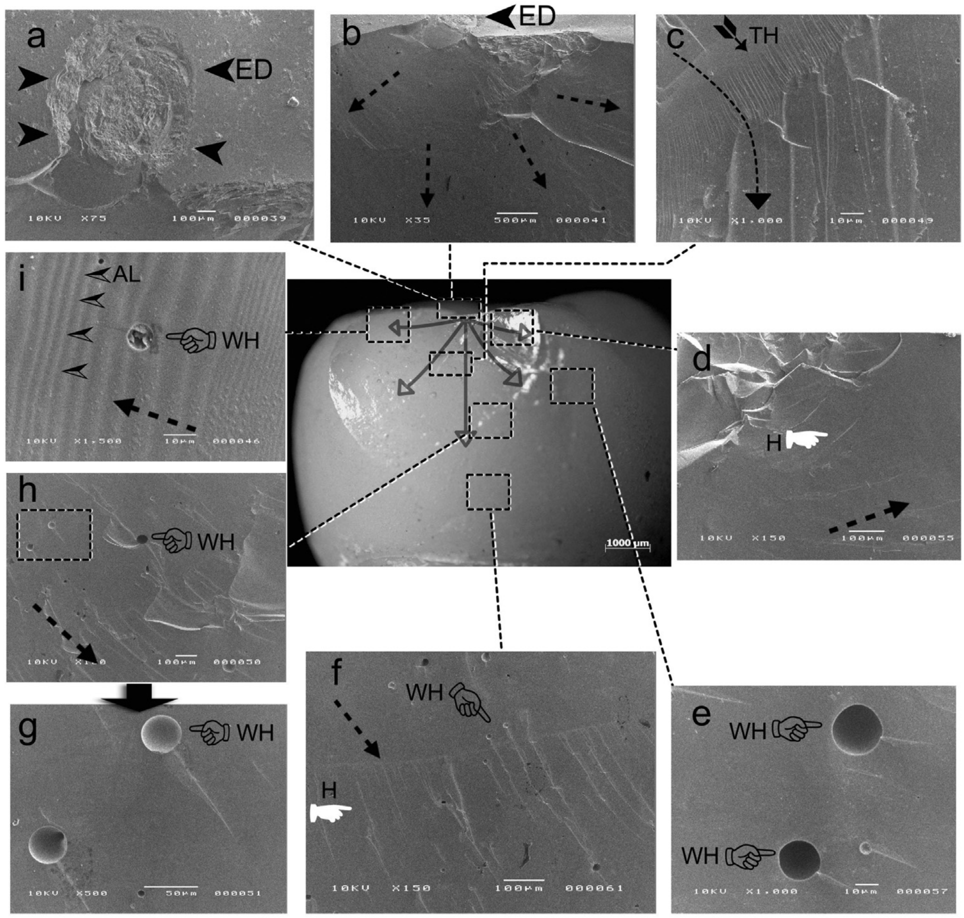

Fig. 3 – Light-polarized microscope (center image) and SEM images (peripheral images) of a representative Bi-EV fractured crown showing the cohesive failure in the veneering porcelain. The fracture began in the indentation area (ED) (a – occlusal view, b – proximal view), and the dashed arrows show the crack propagation toward the buccal, lingual and cervical direction (b). Contact with the indenter (ED) caused the development and coalescence of several micro-cracks leading to quasiplastic deformation. Arrows on center image indicate the direction of fracture propagation, dotted squares indicate areas magnification of peripheral images (SEM) and the dotted arrows indicate the direction of the fracture. SEM show the presence of arrest lines (AL) (i), hackles (H) (d, f), wake-hackles (WK) (e, f, g, h, i), twist-hackles (TH) (c).

4. Discussion

The present study investigated the lifetime of anatomically relevant monolithic and bilayered lithium disilicate crowns with and without core design modification, cemented on dentin-like substrate and subjected to constant stress cyclic loading on marginal ridges in a wet environment. Our hypothesys was partially accepted since monolithic crowns did present the highest overall reliability from 1 to 3 million cycles and mean life, but core design modification did not improve the probability of survival and mean life of bilayered crowns.

As reported in laboratory [1,11–13,61,62] and clinical [16,17,40,63,64] studies, monolithic ceramic crowns used within manufacturer's recommendations thickness tend to perform better compared to veneered crowns. When the low fracture toughness porcelain veneer is eliminated, the fracture toughness of the monolithic bulk material along with its processing methods and thickness will be key to its fatigue performance [13,62]. The processing of lithium disilicate results in a glass-ceramic with fine, elongated grains of approximately 1.5 μm in length and 0.4 μm in diameter of 70% crystal volume incorporated into a glass matrix [65]. These elongated lithium disilicate crystals inhibit crack propagation, and cracking has been shown to occur only through the residual glass phase (30–40% of its volume) [61,65–67]. This microstructure may explain the better tendency of survival of monolithic crowns over the bilayer crowns observed in this and other studies [1,13,62,67], as well as the positive short-term clinical trials results for monolithic lithium disilicate crowns [16,17,40,63,64].

The bilayered crowns had most of the failures restricted to the porcelain veneer, but in a few cases, the core/veneer interface was exposed. In all cases the fracture origin was the indenter contact surface, as previously reported [11,12]. Irrespective of core design modification of bilayered crowns, reliability was significantly lower than that of monolithic

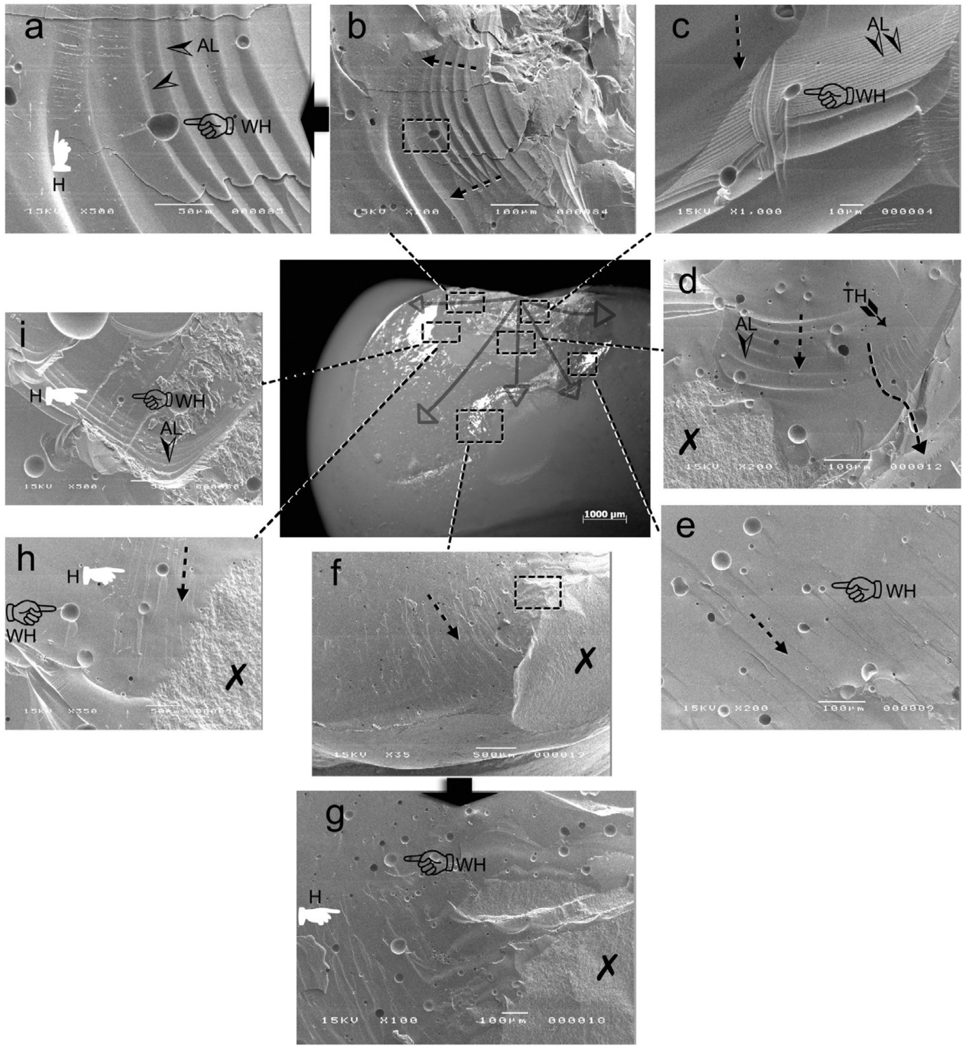

Fig. 4 – Light-polarized microscopic (center image) and SEM micrographs (peripheral images) of a representative failure of a Bi-M crown showing the assembly and qualitative fractographic interpretation of cohesive failure in the veneering porcelain reaching the supporting proximal strut. The fracture started at the point of contact with the indenter propagating on the proximal surface toward the buccal and lingual with fracture of part of the proximal struts. Arrows on center image indicate the direction of fracture propagation, dotted squares indicate areas magnified in peripheral images (SEM) and the dotted arrows indicate the direction of the fracture. SEM indicated the presence of arrest lines (AL) (a, c, d, i), hackles (H) (a, f, g, h, i), wake-hackles (WK) (a, c, e, g, h, i), twist hackles (TH) (d). The dotted arrow in (d) associated with twist-hackle indicates the change of direction of the fracture after suffering axis rotation. The presence of core surface (X) may be observed in images (d, f, g, h), where in (f and g) correspond to failure of the proximal struts.

crowns, implying that veneer application had a significant effect on lifetime. Under accelerated fatigue lifetime testing [13] the highest reliability have been observed for monolithic lithium disilicate crowns (1 mm and 2 mm occlusal thickness) compared to any all-ceramic veneered system. Zhao et al. [12] showed that fatigue was an accelerating factor for monolithic lithium disilicate specimens, but not for bilayered ones, when cyclic fatigue was followed by single-load to failure testing, although final fracture loads were always higher on monolithic relative to bilayered systems. Our results originated from constant stress fatigue testing until failure are in agreement with previously published data using step-stress accelerated life testing (SSALT) [13,62], where failure occurred during fatigue and not from a static compressive load leading to catastrophic failure. As illustrated in the fractographic analyses, failures confined to the porcelain veneer or cohesive within the lithium disilicate material seem to more likely represent the clinical scenario simulated here in constant stress fatigue and SSALT elsewhere [68], regardless of loading location.

Occlusal contacts between teeth may occur between centric cusp and the central pit and marginal ridge [34–37,58]. Occlusal contacts at marginal ridges seem to be present in approximately 37% of the natural dentition [58]. The location of occlusal contacts has been suggested as a critical factor for chipping occurrence [23,24] and clinical failures observed

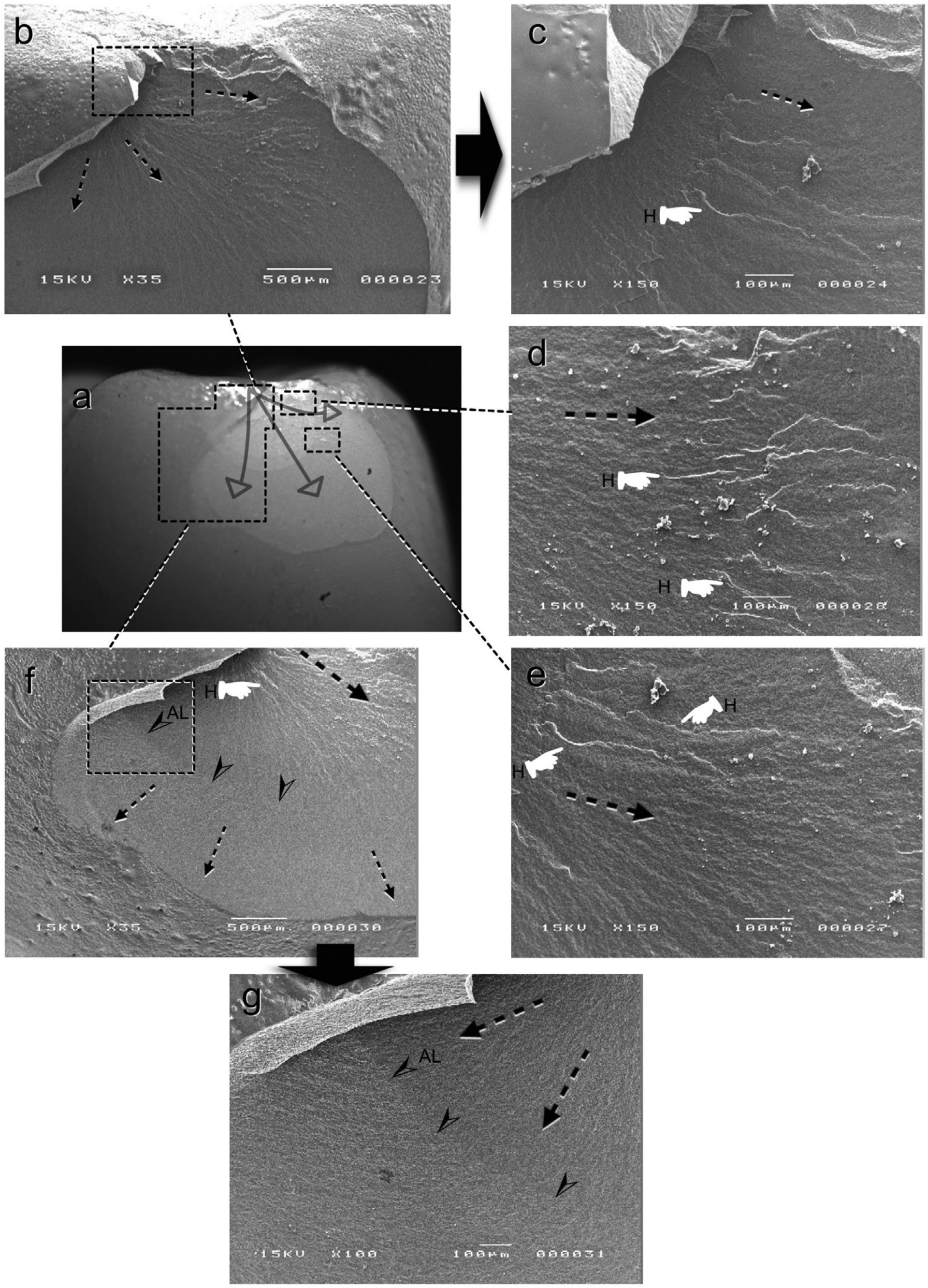

Fig. 5 – Light-polarized microscopic (a) and SEM micrographs (b, c, d, e, f) of a representative fracture of a MON crown showing the assembly and qualitative fractographic interpretation of cohesive failure in the lithium disilicate ceramic. The fracture started at the point of contact with the indenter propagating on the buccal and lingual direction, a small fragment of marginal ridge was still adhered to the crown. Arrows on the image (a) indicate the propagation of the fracture, dotted squares indicate areas magnified in the SEM images and the dotted arrows indicate the direction of the fracture. It is possible to see in the image (b) fractographic traces emerging immediately after the marginal ridge fragment indicating that cracks originated under the contact with the indenter. SEM images show the presence of arrest lines (AL) (f, g) and hackles (H) (c, d, e, f).

in ceramic crowns are frequently located on marginal ridges [20,21,23,24,39–48]. At marginal ridges, porcelain veneering is mostly unsupported by the core when the conventional core design is used, which may hamper the performance of the crown. Therefore, several authors have suggested the modification of core design for metal-ceramic crowns since the 60 s [69–71], or even eliminating all occlusal contacts on distal and mesial marginal ridges for preventing fractures [24].

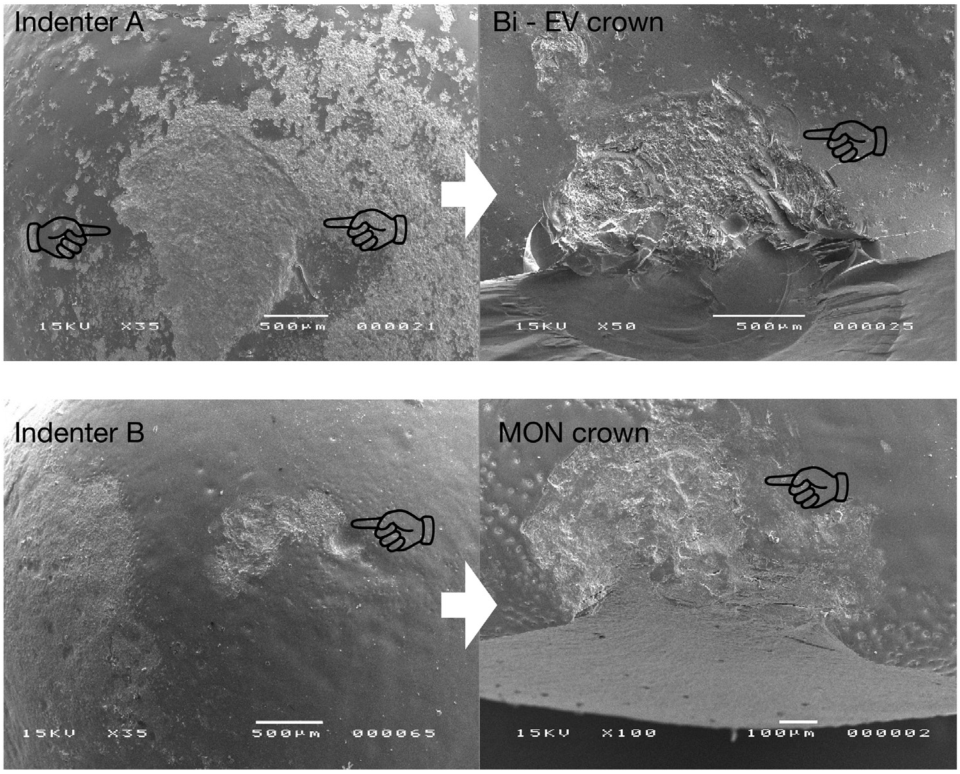

Fig. 6 – SEM micrograph showing the damaged surface of an indenter and respectively fatigued crown. Contact with the indenter caused a surface wear only on the contact area (Image A – pointer) when it was indented with a bilayered crown. The surface of the indented veneering porcelain (Bi-EV crown) showed (pointer) more severe wear than the indenter, due to quasiplastic deformation. When it was analyzed in the monolithic crowns (MON), the contact caused surface wear on the indenter (indenter B pointer) restricted to the contact increasing the roughness. The marginal ridge of the MON showed a quasiplastic deformation similar to the indenter.

One reported benefit of core design modification is the decrease of chipping extension (porcelain fused to Y-TZP crowns) when submitted to fatigue [5,13,27–30]. Our findings on lithium disilicate crowns did not identify such differences when core design modification was applied compared to the conventional design. Several fractures of Bi-M group exposed the proximal struts and/or the lingual collar, suggesting that the design modification used failed to provide support to the veneering porcelain and reduce fracture size, as observed in other studies involving metal-ceramic and zirconia crowns [5,13,20,21,27–31,62,72]. Altogether, it is suggested that the concept of support for porcelain veneer continues empirical since its conception and is sensitive to the class of all-ceramic system under investigation.

When a core is veneered with porcelain resulting in a bilayered restoration, its final strength will always be lower when compared to a monolithic high strength ceramic material, as showed in this and other studies [9,10,73,74]. The use of monolithic systems reduces the mentioned problems [11,12], because it eliminates the veneer application and their complex interfaces. Therefore, because it is composed by only one material, a much less complex structure is expected [62]. LDG has superior mechanical properties such as strength (400 MPa), toughness (2.75 $MPa.m^{1/2}$) and hardness (5.8 GPa) relative to the veneer porcelain (strength 90 MPa; toughness 0.9–1.5 $MPa.m^{1/2}$, and hardness 5.4 GPa) [41].

Moreover, the applied load level was up to 300 N, much lower than those reported in other studies [5,11–13,73,75,76]. The SEM analysis showed markings (hackles, wake-hackles, twist-hackles and arrest lines) that allows to infer the origin and the direction of crack propagation (contact load), as previously illustrated [12,13,22,23,45,46,60,63,77,78]. Furthermore, fractographic analyses performed from clinically fractured crowns revealed the presence of the same patterns and characteristics found here [12,22,24,45,46,60,63,77,78].

The composite resin tooth replicas were used in this study, instead of real teeth, to standardize dimensions and mechanical properties of samples simulating prepared teeth. The modulus of elasticity of composite resin (16 GPa) [79] is close to that of human dentin (18 GPa) [80].

5. Conclusion

Monolithic lithium disilicate crowns presented higher probability of survival and mean life than bilayered crowns with modified framework design when loaded at marginal ridges.

Acknowledgements

Grants from FAPESP grant # 2012/19078-7, 2016/18818-8 and CNPq # 304589/2017-9, 434487/2018-0 and CAPES # 1013072 and # 001. We thank the LAAF dental laboratory – Dourados for crown fabrication. The authors acknowledge Hitachi >S3500N SEM imaging that was made possible by the New York University College of Dentistry's cooperative agreement with the NIH/NIDCR.

REFERENCES

[1] Silva NR, Thompson VP, Valverde GB, Coelho PG, Powers JM, Farah JW, et al. Comparative reliability analyses of zirconium oxide and lithium disilicate restorations in vitro and in vivo. J Am Dent Assoc 2011;142(Suppl 2):4S–9S.

[2] Gehrt M, Wolfart S, Rafai N, Reich S, Edelhoff D. Clinical results of lithium-disilicate crowns after up to 9 years of service. Clin Oral Investig 2013;17:275–84.

[3] Spies BC, Pieralli S, Vach K, Kohal RJ. CAD/CAM-fabricated ceramic implant-supported single crowns made from lithium disilicate: final results of a 5-year prospective cohort study. Clin Implant Dent Relat Res 2017;19:876–83.

[4] Fehmer V, Muhlemann S, Hammerle CH, Sailer I. Criteria for the selection of restoration materials. Quintessence Int 2014;45:723–30.

[5] Silva NR, Bonfante EA, Rafferty BT, Zavanelli RA, Rekow ED, Thompson VP, et al. Modified Y-TZP core design improves all-ceramic crown reliability. J Dent Res 2011;90:104–8.

[6] Molin MK, Karlsson SL. Five-year clinical prospective evaluation of zirconia-based Denzir 3-unit FPDs. Int J Prosthodont 2008;21:223–7.

[7] Tinschert J, Schulze KA, Natt G, Latzke P, Heussen N, Spiekermann H. Clinical behavior of zirconia-based fixed partial dentures made of DC-Zirkon: 3-year results. Int J Prosthodont 2008;21:217–22.

[8] Bona AD, Anusavice KJ, DeHoff PH. Weibull analysis and flexural strength of hot-pressed core and veneered ceramic structures. Dent Mater 2003;19:662–9.

[9] Taskonak B, Anusavice KJ, Mecholsky Jr JJ. Role of investment interaction layer on strength and toughness of ceramic laminates. Dent Mater 2004;20:701–8.

[10] Taskonak B, Mecholsky Jr JJ, Anusavice KJ. Residual stresses in bilayer dental ceramics. Biomaterials 2005;26:3235–41.

[11] Zhao K, Pan Y, Guess PC, Zhang XP, Swain MV. Influence of veneer application on fracture behavior of lithium-disilicate-based ceramic crowns. Dent Mater 2012;28:653–60.

[12] Zhao K, Wei YR, Pan Y, Zhang XP, Swain MV, Guess PC. Influence of veneer and cyclic loading on failure behavior of lithium disilicate glass-ceramic molar crowns. Dent Mater 2014;30:164–71.

[13] Silva NR, Bonfante EA, Martins LM, Valverde GB, Thompson VP, Ferencz JL, et al. Reliability of reduced-thickness and thinly veneered lithium disilicate crowns. J Dent Res 2012;91:305–10.

[14] Aboushelib MN, Kleverlaan CJ, Feilzer AJ. Microtensile bond strength of different components of core veneered all-ceramic restorations. Part II: Zirconia veneering ceramics. Dent Mater 2006;22:857–63.

[15] Lenz J, Thies M, Schweizerhof K. In the service of the crown. German Res 2002;24:30–3.

[16] Fasbinder DJ, Dennison JB, Heys D, Neiva G. A clinical evaluation of chairside lithium disilicate CAD/CAM crowns: a two-year report. J Am Dent Assoc 2010;141(Suppl 2): 10S–4S.

[17] Reich S, Fischer S, Sobotta B, Klapper HU, Gozdowski S. A preliminary study on the short-term efficacy of chairside computer-aided design/computer-assisted manufacturing-generated posterior lithium disilicate crowns. Int J Prosthodont 2010;23:214–6.

[18] White SN. Mechanical fatigue of a feldspathic dental procelain. Dent Mater 1993;9:260–4.

[19] Wiskott HW, Nicholls JI, Belser UC. Stress fatigue: basic principles and prosthodontic implications. Int J Prosthodont 1995;8:105–16.

[20] Marchack BW, Futatsuki Y, Marchack CB, White SN. Customization of milled zirconia copings for all-ceramic crowns: a clinical report. J Prosthet Dent 2008;99:169–73.

[21] Marchack BW, Sato S, Marchack CB, White SN. Complete and partial contour zirconia designs for crowns and fixed dental prostheses: a clinical report. J Prosthet Dent 2011;106:145–52.

[22] Scherrer SS, Quinn JB, Quinn GD, Kelly JR. Failure analysis of ceramic clinical cases using qualitative fractography. Int J Prosthodont 2006;19:185–92.

[23] Koenig V, Vanheusden AJ, Le Goff SO, Mainjot AK. Clinical risk factors related to failures with zirconia-based restorations: an up to 9-year retrospective study. J Dent 2013;41:1164–74.

[24] Moraguez OD, Wiskott HW, Scherrer SS. Three- to nine-year survival estimates and fracture mechanisms of zirconia- and alumina-based restorations using standardized criteria to distinguish the severity of ceramic fractures. Clin Oral Investig 2015;19(December (9)):2295–307.

[25] McLean JW. Tooth preparation an the design of metal substructures. Dent Ceram Quintessence 1983:173–87.

[26] Schmitter M, Mussotter K, Rammelsberg P, Stober T, Ohlmann B, Gabbert O. Clinical performance of extended zirconia frameworks for fixed dental prostheses: two-year results. J Oral Rehabil 2009;36:610–5.

[27] Guess PC, Bonfante EA, Silva NR, Coelho PG, Thompson VP. Effect of core design and veneering technique on damage and reliability of Y-TZP-supported crowns. Dent Mater 2013;29:307–16.

[28] Lorenzoni FC, Martins LM, Silva NR, Coelho PG, Guess PC, Bonfante EA, et al. Fatigue life and failure modes of crowns systems with a modified framework design. J Dent 2010;38:626–34.

[29] Paula VG, Lorenzoni FC, Bonfante EA, Silva NR, Thompson VP, Bonfante G. Slow cooling protocol improves fatigue life of zirconia crowns. Dent Mater 2015;31:77–87.

[30] Silva NR, Bonfante E, Rafferty BT, Zavanelli RA, Martins LL, Rekow ED, et al. Conventional and modified veneered zirconia vs. metalloceramic: fatigue and finite element analysis. J Prosthodont 2012;21:433–9.

[31] Fardin VP, de Paula VG, Bonfante EA, Coelho PG, Bonfante G. Lifetime prediction of zirconia and metal ceramic crowns loaded on marginal ridges. Dent Mater 2016;32:1543–54.

[32] Miura S, Kasahara S, Yamauchi S, Okuyama Y, Izumida A, Aida J, et al. Clinical evaluation of zirconia-based all-ceramic single crowns: an up to 12-year retrospective cohort study. Clin Oral Investig 2018;22:697–706.

[33] Simeone P, Gracis S. Eleven-year retrospective survival study of 275 veneered lithium disilicate single crowns. Int J Periodontics Restorative Dent 2015;35:685–94.

[34] Occlusion Friel S. Observations on its development from infancy to old age International Journal of Orthodontia. Int J Orthodont Oral Surg Radiogr 1927;13:322–43.

[35] Myers GE, Anderson Jr JR. Nature of contacts in centric occlusion in 32 adults. J Dent Res 1971;50:7–13.

[36] Benazzi S, Kullmer O, Grosse IR, Weber GW. Using occlusal wear information and finite element analysis to investigate

stress distributions in human molars. J Anat 2011;219:259–72.
[37] Benazzi S, Grosse IR, Gruppioni G, Weber GW, Kullmer O. Comparison of occlusal loading conditions in a lower second premolar using three-dimensional finite element analysis. Clin Oral Investig 2014;18:369–75.
[38] Palamara JE, Palamara D, Messer HH. Strains in the marginal ridge during occlusal loading. J Aust Dent 2002;47:218–22.
[39] Aboushelib MN, Feilzer AJ, Kleverlaan CJ. Bridging the gap between clinical failure and laboratory fracture strength tests using a fractographic approach. Dent Mater 2009;25:383–91.
[40] Etman MK, Woolford MJ. Three-year clinical evaluation of two ceramic crown systems: a preliminary study. J Prosthet Dent 2010;103:80–90.
[41] Guess PC, Schultheis S, Bonfante EA, Coelho PG, Ferencz JL, Silva NR. All-ceramic systems: laboratory and clinical performance. Dent Clin North Am 2011;55:333–52, ix.
[42] Harder S, Wolfart S, Eschbach S, Kern M. Eight-year outcome of posterior inlay-retained all-ceramic fixed dental prostheses. J Dent 2010;38:875–81.
[43] Kim JH, Kim JW, Myoung SW, Pines M, Zhang Y. Damage maps for layered ceramics under simulated mastication. J Dent Res 2008;87:671–5.
[44] Lohbauer U, Kramer N, Petschelt A, Frankenberger R. Correlation of in vitro fatigue data and in vivo clinical performance of a glassceramic material. Dent Mater 2008;24:39–44.
[45] Oilo M, Hardang AD, Ulsund AH, Gjerdet NR. Fractographic features of glass-ceramic and zirconia-based dental restorations fractured during clinical function. Eur J Oral Sci 2014;122:238–44.
[46] Scherrer SS, Quinn JB, Quinn GD, Wiskott HW. Fractographic ceramic failure analysis using the replica technique. Dent Mater 2007;23:1397–404.
[47] Sorrentino R, De Simone G, Tete S, Russo S, Zarone F. Five-year prospective clinical study of posterior three-unit zirconia-based fixed dental prostheses. Clin Oral Investig 2012;16:977–85.
[48] Zhang Y, Chai H, Lee JJ, Lawn BR. Chipping resistance of graded zirconia ceramics for dental crowns. J Dent Res 2012;91:311–5.
[49] Huang M, Thompson VP, Rekow ED, Soboyejo WO. Modeling of water absorption induced cracks in resin-based composite supported ceramic layer structures. J Biomed Mater Res B Appl Biomater 2008;84:124–30.
[50] HotWire R. Determining the Sample Size for a Life Test Based on the Shape Parameter of the Weibull Distribution. Resources WcRE, editor. Issue 126 ed. https://www.weibull.com/hotwire/issue126/hottopics126.htm2018.
[51] Meeker WQ, Escobar LA. Statistical methods for reliability data. John Wiley & Sons; 2014.
[52] Nelson WB. Accelerated testing statistical models, test plans, and data analysis. New York: John Wiley & Sons; 2004.
[53] AG IV. IPS e. max Press Monolithic Solutions. Ivoclar Vivadent AG, Schaan/Liechtenstein. 2017.
[54] Nakashima J, Taira Y, Sawase T. In vitro wear of four ceramic materials and human enamel on enamel antagonist. Eur J Oral Sci 2016;124:295–300.
[55] Ehrlich J, Taicher S. Intercuspal contacts of the natural dentition in centric occlusion. J Prosthet Dent 1981;45:419–21.
[56] Hochman N, Ehrlich J. Tooth contact location in intercuspal position. Quintessence Int 1987;18:193–6.
[57] Pokorny DK. Current procedures in fixed prosthodontics. Dent Clin North Am 1971;15:685–710.
[58] Watanabe-Kanno GA, Abrão J. Study of the number of occlusal contacts in maximum intercuspation before orthodontic treatment in subjects with Angle Class I and Class II Division 1 malocclusion. Dental Press J Orthod 2012;17:138–47.
[59] Wiskott HW, Belser UC. A rationale for a simplified occlusal design in restorative dentistry: historical review and clinical guidelines. J Prosthet Dent 1995;73:169–83.
[60] Quinn GD. Fractography of ceramics and glasses. Washington, DC: National Institute of Standards and Technology; 2007.
[61] Anusavice KJ, Jadaan OM, Esquivel-Upshaw JF. Time-dependent fracture probability of bilayer, lithium-disilicate-based, glass-ceramic, molar crowns as a function of core/veneer thickness ratio and load orientation. Dent Mater 2013;29:1132–8.
[62] Guess PC, Zavanelli RA, Silva NR, Bonfante EA, Coelho PG, Thompson VP. Monolithic CAD/CAM lithium disilicate versus veneered Y-TZP crowns: comparison of failure modes and reliability after fatigue. Int J Prosthodont 2010;23:434–42.
[63] Guess PC, Selz CF, Steinhart YN, Stampf S, Strub JR. Prospective clinical split-mouth study of pressed and CAD/CAM all-ceramic partial-coverage restorations: 7-year results. Int J Prosthodont 2013;26:21–5.
[64] Fabbri G, Zarone F, Dellificorelli G, Cannistraro G, De Lorenzi M, Mosca A, et al. Clinical evaluation of 860 anterior and posterior lithium disilicate restorations: retrospective study with a mean follow-up of 3 years and a maximum observational period of 6 years. Int J Periodontics Restorative Dent 2014;34:165–77.
[65] Guazzato M, Albakry M, Ringer SP, Swain MV. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part I. Pressable and alumina glass-infiltrated ceramics. Dent Mater 2004;20:441–8.
[66] Apel E, Deubener J, Bernard A, Holand M, Muller R, Kappert H, et al. Phenomena and mechanisms of crack propagation in glass-ceramics. J Mech Behav Biomed Mater 2008;1: 313–25.
[67] Denry I, Holloway JA. Ceramics for dental applications: a review. Mater Mol Divers Preserv Int 2010;3:351–68.
[68] Bonfante EA, Coelho PG. A critical perspective on mechanical testing of implants and prostheses. Adv Dent Res 2016;28:18–27.
[69] Seghi RR, Daher T, Caputo A. Relative flexural strength of dental restorative ceramics. Dent Mater 1990;6:181–4.
[70] Straussberg G, Katz G, Kuwata M. Design of gold supporting structures for fused porcelain restorations. J Prosthet Dent 1966;16:928–36.
[71] Shelby DS. Practical considerations and design of the porcelain fused to metal. J Prosthet Dent 1962;12:542–8.
[72] Bonfante EA, da Silva NR, Coelho PG, Bayardo-Gonzalez DE, Thompson VP, Bonfante G. Effect of framework design on crown failure. Eur J Oral Sci 2009;117:194–9.
[73] Johansson C, Kmet G, Rivera J, Larsson C, Vult Von Steyern P. Fracture strength of monolithic all-ceramic crowns made of high translucent yttrium oxide-stabilized zirconium dioxide compared to porcelain-veneered crowns and lithium disilicate crowns. Acta Odontol Scand 2014;72:145–53.
[74] Wei YR, Pan Y, Cao SS, Zhang XP, Zhao K. Influence of veneer application on failure behavior and reliability of lithium disilicate glass-ceramic molar crowns. Zhonghua Kou Qiang Yi Xue Za Zhi 2013;48:91–5.
[75] Seydler B, Rues S, Muller D, Schmitter M. In vitro fracture load of monolithic lithium disilicate ceramic molar crowns with different wall thicknesses. Clin Oral Investig 2014;18:1165–71.
[76] Zesewitz TF, Knauber AW, Northdurft FP. Fracture resistance of a selection of full-contour all-ceramic crowns: an in vitro study. Int J Prosthodont 2014;27:264–6.

[77] Oilo M, Gjerdet NR. Fractographic analyses of all-ceramic crowns: a study of 27 clinically fractured crowns. Dent Mater 2013;29:e78–84.
[78] Scherrer SS, Quinn GD, Quinn JB. Fractographic failure analysis of a Procera AllCeram crown using stereo and scanning electron microscopy. Dent Mater 2008;24:1107–13.
[79] Kim B, Zhang Y, Pines M, Thompson VP. Fracture of porcelain-veneered structures in fatigue. J Dent Res 2007;86:142–6.
[80] Lawn BR, Deng Y, Lloyd IK, Janal MN, Rekow ED, Thompson VP. Materials design of ceramic-based layer structures for crowns. J Dent Res 2002;81:433–8.