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Failure probability of three designs of zirconia crowns

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Abstract

Objectives—This study utilized a 2-parameter Weibull analysis for evaluation of lifetime of fully or partially porcelain-/glaze-veneered zirconia crowns after fatigue test.

Methods—Sixty first molars were selected and prepared for full-coverage crowns with three different designs ($n = 20$): Traditional—crowns with zirconia framework covered with feldspathic porcelain; Modified—crowns partially covered with veneering porcelain; and Monolithic—full-contour zirconia crowns. All specimens were treated with a glaze layer. Specimens were subjected to mechanical cycling (100N, 3Hz) with a piston with hemispherical tip ($\varnothing = 6$ mm) until the specimens failed or up to 2×10^6 cycles. Every 500,000 cycles intervals, the fatigue tests were interrupted, and stereomicroscopy (10 X) was used to inspect the specimens for damage. We performed Weibull analysis of interval data to calculate the number of failures in each interval.

Results—The types and number of failures according to the groups were: cracking (Traditional-13, Modified-6) and chipping (Traditional-4) of the feldspathic porcelain, followed by delamination (Traditional-1) at the veneer/core interface and debonding (Monolithic-2) at the cementation interface. Weibull parameters (beta, scale; and eta, shape), with a two-sided confidence interval of 95%, were: Traditional – 1.25 and 0.9×10^6 cycles; Modified– 0.58 and 11.7×10^6 cycles; and Monolithic – 1.05 and 16.5×10^6 cycles. Traditional crowns showed greater susceptibility to fatigue, the Modified group presented higher propensity to early failures, and the Monolithic group showed no susceptibility to fatigue. The Modified and Monolithic groups presented the highest number of crowns with no failures after the fatigue test.

Conclusions—The three crown designs presented significantly different behaviors under fatigue. The Modified and the Monolithic groups presented less probability to failure after 2×10^6 cycles.

Keywords

zirconia; crown; fatigue damage; failure probability; weibull analysis

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1.Introduction

All-ceramic restorations are widely used due to their excellent mechanical and aesthetic properties. Zirconia is used as a framework, and, as it presents relative opacity¹, it is covered with porcelain containing optical properties similar to those of natural teeth.^{2,3} However, this type of restoration has residual stress generated by thermal issues⁴⁻⁶ and hence is susceptible to fracture.⁷ This susceptibility may also be explained by the processing technique^{8,9} or inadequate porcelain support.¹⁰

Clinical studies have reported failures such as chipping (cohesive failure of porcelain) and delamination (adhesive failure between the ceramic cover and infrastructure).¹¹⁻¹³ To optimize the performance of these restorations, slow cooling¹⁴ and reduced numbers of firings may be used.¹⁵ Also, modification of the crown design has decreased the risk of fracture, particularly by improving porcelain support and consequently increasing the reliability of the restoration.¹⁶

Since it is known clinically that failures of all-ceramic crowns occur when they are subjected to fatigue,^{17,18} laboratory studies of these structures should not only simulate repetitive masticatory effort, but also should be performed in specimens that imitate the dental anatomy, with relevant substrates such as dentin, resin or metal.^{19,20} Moreover, the exposure of zirconia to wet environments should be avoided, as it is subject to hydrothermal degradation, unleashing the transformation of zirconia crystals from tetragonal to monolithic, leading to fracture.^{21,22} In this sense, therefore, the veneering porcelain protects the zirconia framework from hydrothermal degradation.

A thin glass layer over the zirconia surface, such as a full-contour crown, can also protect the zirconia restoration and minimize the occurrence of fractures arising from the porcelain coating.²³⁻²⁵ Furthermore, it is believed that modifying the crown design can minimize the occurrence of failures, increasing the restoration's survivability when it is under fatigue. Therefore, this study utilized Weibull probability plots to evaluate the failure probability of fully or partially porcelain-/glaze-veneered crowns after cyclic fatigue. The null hypothesis was that there were no significant differences in fatigue damage tolerance among the three crown designs.

2. Materials and methods

2.a. Material

Materials used in this study are listed in Table 1.

2.b. Methods

2.b.1.Specimen preparation—This study received the approval of the ethics committee of the Institute of Science and Technology of São José dos Campos- State University of São Paulo on 28/03/2013 (Process #12486313.4.0000.0077). Sixty intact first molars were cleaned with 2% chloramine and stored in distilled water. Teeth were embedded by the root (up to 2 mm below the cemento-enamel junction) in polyurethane with the aid of a device that maintained the long axis perpendicular to the horizontal plane. Diamond burs (4137 and

4137FF, Microdont, São Paulo, São Paulo, Brazil) were used to prepare the teeth for full-contour crowns under high-speed rotation in a modified optical microscope for standardized tooth preparation (1.5 mm axial reduction with complete removal of enamel and 5 mm height from the cement-enamel junction). The prepared teeth were randomized and divided into three groups according to the design of the restoration (Table 2). The preparations were then molded simultaneously with light- and heavy-body silicone (Elite H-D + Light Body Fast and Elite H-D + Putty Soft, Rovigo Italia). The models were obtained with type IV die stone (CAM-based, Dentona AG, Germany) for scanning in the computer unit (CAD), where the restorations (or crowns) were designed in three dimensions (Cerec 3D). Twenty crowns of each design were made from the pre-sintered ceramic blocks (Vita In-Ceram YZ - YZ-40-40 × 15 × 15 mm) (Vita Zahnfabrik, Bad Säckingen, Germany) with an internal relief of 70 µm and then sintered in a Vita ZYrcomat furnace (Vita Zahnfabrik) according to the following schedule: 40°C initial temperature (1 h to final temperature 1530°C); dwell time, 2 h; and cooling temperature at which the tray was lowered in the furnace, 400°C.

The Traditional crowns consisted of a zirconia framework (~ 0.5 mm) covered by veneering porcelain (~ 1.0 mm). Those in the Modified group were zirconia crowns covered with porcelain (~ 1.0 mm) only on the buccal side, slightly extended to the occlusal surface. Those in the Monolithic group were solid zirconia crowns. All crowns were coated with a glaze layer.

For Traditional and Modified groups, two layers of base dentin were applied (VM9 Vita, Vita Zahnfabrik). The firing protocol was: Washburn sintering, initial temperature, 500°C; pre-drying time, 6 min; heating time, 3 min; temperature elevation rate, 33°C/min; final temperature, 700°C; and dwell time at the final temperature, 5 min. The first and second dentin sinterings occurred at: initial temperature, 500°C; pre-drying time, 6 min; heating time, 7.27/7.17 min; temperature elevation rate, 55°C/min; final temperature, 910/900°C; and dwell time at the final temperature, 1 min. A silicon mold (heavy-body) was made from a standard model so that all crowns had approximately the same final dimensions and the anatomy of an upper first molar (~ 1.0-mm-thick feldspathic porcelain). Finishing and polishing of the crowns were performed, and then the glaze layer was applied for all groups (Akzent glaze, Vita Zahnfabrik).

2.b.2. Ceramic surface treatment and cementation—The crown intaglio surface was coated with Monobond Plus (Ivoclar Vivadent, Schaan, Liechtenstein), applied with a microbrush and left undisturbed for 5 min. Before cementation, the teeth were etched with 37% phosphoric acid for 15 s and washed thoroughly with water. Adper Scotchbond Multipurpose adhesive (3M™ ESPE™) was then applied in two layers (primer and adhesive) by means of a microbrush and cured for 20 s. Cementation was performed with Variolink II (Ivoclar Vivadent), whose base and catalyst were applied in equal proportions. The cement was applied on the inner side walls of the crown, which was brought into position and kept under a constant load of 750 g. The assembly was cured for 40 s on the buccal, lingual and occlusal sides (total time, 120 s). The cemented crowns were stored in distilled water for 24 h prior to being fatigue-tested.

2.b.3. Fatigue test—The fatigue test was performed with a piston (diameter, 6 mm) in a fatigue simulator (Biocycle V1, BioPdi, Indústria e Comércio de Equipamentos Médicos e Odontológicos São Carlos, SP, Brazil). Each specimen was positioned in a metal base in a tank filled with distilled water (37°C), forming a 90° angle between the horizontal plane and the piston under the following regimen: load of 100N at a frequency of 3Hz. The piston touched the internal inclines of the buccal and lingual cusps. Each load cycle consisted of the indenter coming into contact with the specimens, loading to a maximum, holding for 0.17 s and completely unloading for 0.16s. In total, 2×10^6 cycles were performed for fatigue testing. To diminish the impact between the indenter and the occlusal surface, a silicon film (1 mm) was positioned on the top surface of the crown. Before simulating chewing cycles, the equipment was calibrated with the pressure necessary to achieve appropriate force. Fatigue tests were interrupted every 500,000 cycles, and the specimens were inspected by stereomicroscopy (stereo Discovery.V12, Carl Zeiss, LLC, USA) for any damage sustained. Chipping of the veneering ceramic, delamination (exposure of zirconia framework), cracks, catastrophic fracture of the restoration and debonding of crowns were considered failures. If none of these was observed, the specimens continued to be subjected to fatigue test until failure or until the test was complete (specimens that survived, showing no failures after 2×10^6 cycles, were considered “suspended” in the analysis). To determine the reliability of all groups, the following Weibull distribution was used:

$$F(t) = 1 - e^{-\left(\frac{t-t_0}{\eta}\right)^\beta} = 1 - \exp\left[-\left(\frac{t-t_0}{\eta}\right)^\beta\right]$$

The shape parameter β value describes failure rate changes over time ($\beta < 1$, failure rate decreases over time, commonly associated with “early failures” or failures that occur due to egregious flaws; $\beta \sim 1$, failure rate does not vary over time, associated with failures of a random ‘nature; and $\beta > 1$, failure rate increases over time, associated with failures related to damage accumulation). The η value describes the scale parameter or characteristic lifetime at which 63.2% of the units will fail. Both parameters are adimensional. The parameters were calculated by the Weibull++ software (Weibull++ 9, Reliasoft, Tucson, AZ, USA), where the reliability was plotted as a function of time, with a bilateral confidence interval (95%). We used Maximum Likelihood Estimation as analysis method and Fisher Matrix method for confidence bound calculation.

The subsurface damage in fractured and suspended specimens was analyzed by means of an embedding and sectioning method²⁶. Specimens were embedded in acrylic resin and sectioned near the contact point. The sectioned crowns were polished with SiC # 600, 800 and 1200; damage sustained was observed by stereomicroscopy (SteREO Discovery. V12, Carl Zeiss). For the crowns with significant failures, after being gold-sputtered (EMITECH, SC6270), surfaces were analyzed by scanning electron microscopy (SEM) (FEI, Phillips, Eindhoven, Netherlands).

3. Results

After failure analysis, the main types of failures were found to be cracking and chipping, followed by delamination at the veneer/core interface and debonding of the crown from the tooth abutment. Data are shown in Table 2. Values of beta (β) and eta (η) of the three tested groups showed behavioral differences for the crowns according to their design (Fig. 1). Table 2 also shows that crowns in the Traditional group had higher failure probability due to fatigue. Those in the Modified and Monolithic groups had early failures and random failures, respectively, as expressed by their β parameters. Table 2 summarizes the relation between numbers and groups of failed crowns at each time interval (cycles).

Considering the same cycling regime (frequency and load), the rate and failure probability were predicted for 5 years and are described in Table 3.

The majority of crowns presented cracks that originated on the contact surface (Fig. 2). One Modified-design crown showed that the crack originated below the occlusal surface at the porcelain/zirconia interface (Fig. 3). Fig. 4 shows a Monolithic crown, which presented none of the outcomes that the authors considered as failures.

4. Discussion

This research examined three different framework designs for all-ceramic full-coverage crowns, with the goal of increasing the reliability and decreasing the failure probability of the systems. Based on the results obtained from this study, the three tested groups did present different lifetimes, causing us to reject the anticipated null hypothesis. Despite the excellent mechanical properties of the framework material, the all-ceramic crowns presented chipping failures of the porcelain (Fig. 3). Figs. 2 and 3 also display the predominance of cracks in porcelain as a mode of failure. Nevertheless, cracks are usually considered non-catastrophic failures and can be clinically corrected by polishing or repair.

Table 2 displays the number of “wear” failures found in the Traditional group ($\beta > 1$). These crowns experienced damage related to the test. Thus, it is possible to affirm that crowns were well-manufactured, without the inclusion of major defects that could lead to premature failure. Conversely, crowns from the Modified group presented premature failures, indicating that the pieces failed even before fatigue could damage the structure. These premature failures may be caused by the inclusion of defects during porcelain application, or because, despite the fact that the load applicator tip was adjusted to come into contact at three points without touching the zirconia/porcelain interface, the damage generated by the test was extended to the interface, leading to premature failure of the crowns. This may represent a limitation of the Modified design. The Monolithic crowns presented a random type of failure, which indicates that the fatigue test was not able to cause detectable damage. Failures found for this crown design were related to crown detachment, but not to fatigue fracture.

Regarding the lifetime analysis of the crowns, those in the traditionally designed group presented higher failure predictability. Modified and Monolithic crowns presented longer lifetimes but lower predictability of cycles to failure.

The Modified and Monolithic groups included higher numbers of specimens that survived the fatigue test. When a modification is performed at the preparation of the framework for full crowns, there is usually an optimisation of porcelain support.^{10,16} When a monolithic design is applied to the crown, its tolerance to damage is increased, presenting a behavior similar to that of metallic crowns.²⁷ This study confirmed this fact, as Modified and Monolithic crowns presented characteristic lifetimes far beyond the number of cycles proposed in the study; the modifications contributed to the restorations' durability.

Silva et al (2010)¹⁶ and Bonfante (2010)²⁸ also showed that the alteration of the restoration's design increased the porcelain support, decreasing the number of cohesive failures (Table 2). It is important to point out that the Modified design proposed here has not been previously investigated and may provide excellent aesthetic results and clinical survival rates. In this model of crown design, the proximal and occlusal extensions of the porcelain are kept to a minimum, decreasing the failure probability in these areas, which are considered critical for failure.²⁹

Clinical studies showed high survival rates of 74% in the first five years; however, there are several reports of failure by chipping and delamination in traditional restorations.^{13,30} This indicates that the highest failure rate found in the Traditional group was expected, mainly because more porcelain and probably more thermal stresses are trapped in the restorations due to thermal issues between the zirconia framework and porcelain,^{4,8,10,28,31,6} making it more susceptible to cracking.⁷ Thus, the Modified and Monolithic crowns behaved differently from Traditional crowns.

In the present study, it was also possible to predict the failure probability in five years and failure rate by year (Table 3), showing that the Modified and Monolithic groups presented very low probability compared with the Traditional group.

According to fractographic analysis, the Traditional crowns presented the same pattern of failure, as all specimens were subjected to the same type of test with cracks starting from the contact point. The Modified crowns presented cracks starting at the interface between the zirconia and porcelain, which seemed to be the Achilles heel of this type of crown. In spite of that, only six out of 20 Modified crowns failed. The fatigue model used herein can be considered innocuous to Monolithic crowns, and its weakest link seems to be the bonding interface between zirconia and the adhesive cement.

Laboratory studies should simulate actual clinical conditions; therefore, it is relevant that the fatigue test was conducted in humid conditions. A silicon film was used, interposed between the applicator tip and the occlusal surface, as in chewing cycles there is a food bolus between the tooth and the opposite occlusal surface. In this case, the effect of the impact was minimised in the crown due to simulated movement wherein the tip was out of contact with the occlusal surface, as in masticatory movement.

Crowns were tested in distilled water at 37°C, and therefore we were careful not to expose zirconia by glazing all crowns. The solid zirconia crowns did not fracture but were damaged in the subsurface, indicating that the glaze was removed during the fatigue test.

The porcelain, despite being the weakest link of all-ceramic restorations, also helps protect zirconia against hydrothermal degradation and therefore was used in the Modified and Traditional design types. This degradation also occurs with porcelain, due to the polarity of water that contributes to slow crack growth³² and this fact also explains the greater number of failures with the Traditional design.

Future studies should be performed modifying the designs of the crowns and testing them under sliding fatigue, which is likely a more clinically relevant fatigue model.³³

5. Conclusions

According to the methodology applied in the study and the results obtained, it was concluded that:

- 1) the three designs of restoration presented different behaviors under fatigue;
- 2) the Modified crown design, despite showing early failures, had lower susceptibility to fatigue damage than the Traditional crown design; and
- 3) the solid zirconia crown (Monolithic) did not show any susceptibility to fatigue failure.

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Fig. 1. Probability of failure x time (number of cycles) plot of the tested groups: Traditional, Modified and Monolithic. The blue line represents the failure probability of the respective group with a 95% level of bilateral confidence. Red lines indicate the confidence interval.

Fig.2.

SEM images (left side – 115× magnification) and stereomicroscopy images (right side - 7.5× magnification) of a Traditional crown. The crack origin is located at the contact surface of the crown. The failure was recorded at 10^6 cycles. Arrows indicate the crack below the occlusal contact, at the subsurface.

Fig. 3.

SEM images (left side – 115× magnification) and stereomicroscopy images (right side - 7.5× magnification) of the Modified and Traditional crowns. Images show a crack far from the contact area starting at the interface and moving buccally before fracture. The failure was recorded at 10^6 cycles.

Fig. 4. SEM images (left side – 1,000 $\times$ magnification) and stereomicroscopy images (right side - 7.5 $\times$ magnification) of the Monolithic crown. The SEM image, performed with backscattered electrons, shows damage at the subsurface of a surviving crown.

Table 1

Materials for execution of this study.

Materials	Tradename	Manufacturer
Yttria-stabilised tetragonal zirconia (Y-TZP)	InCeram YZ	Vita Zahnfabrik, Bad Säckingen, Germany
Resin cement	Variolink II	Ivoclar Vivadent AG, Schaan, Liechtenstein
MDP-based primer	MONOBOND PLUS	Ivoclar Vivadent AG, Schaan, Liechtenstein
Feldspathic ceramic	VM9	Vita Zahnfabrik, Bad Säckingen, Germany
Glaze	Vita Akzent	Vita Zahnfabrik, Bad Säckingen, Germany
37% Phosphoric acid	CONDAC	Condac porcelana-FGM, Joinville, Santa Catarina, Brazil
Adhesive 2-step	Adhesive Systems Adper Scotchbond Multi-Purpose	3M ESPE, Seefeld, Germany
Polyurethane	F16 POLYOL e F16-F17 ISSO	Axson Brazil Technologies- São Paulo, Brazil

Table 2

Numbers and types of failure for each time interval (cycle) and β and η values for the three tested groups.

	500,000	1,000,000	1,500,000	2,000,000	B	η
Traditional	7 (6 C, 1 Ch)	7 (5 C, 2 Ch)	4 (2 C, 1 Ch, 1 D)	0	1.25	0,09E+07cycles
Modified	3 (3 C)	1 (1 C)	1 (C)	1 (C)	0.58	1.17E+07 cycles
Monolithic	0	2 (CD)	0	0	1.05	1.65E+07 cycles

C, cracks; Ch, chipping; D, delamination; CD, crown displacement.

Table 3

Failure probability in five years and failure rate per year.

	5-year failure probability	Failure rate
Traditional	0.022 (SL, 0.15; IL, 0.003)	0.005/year (SL, 0.03; IL, 0.001)
Modified	0.037 (SL, 0.37; IL, 0.003)	0.004/year (SL, 0.02; IL, 0.0009)
Monolithic	0.002 (SL, 0.23; IL, 0.000007)	0.0004/year (SL, 0.02; IL, 0.000006)

SL, superior limit; IL, inferior limit,