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# Fatigue Resistance of Y-TZP/Porcelain Crowns is Not Influenced by the Conditioning of the Intaglio Surface

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## Clinical Relevance

In this study, very few Y-TZP frameworks failed, but the porcelain veneers frequently chipped. Cementing with an adhesive resin cement helped veneers survive larger fatigue loads without chipping. Treatment of the intaglio surface of the crowns neither helped nor hurt fatigue resistance.

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## SUMMARY

**Objectives:** The objective of this study was to investigate the effects of treatments of the intaglio surface of Y-TZP frameworks and luting agents on the fatigue resistance of all-ceramic crowns.

**Methods:** A research design was chosen that attempted to reduce the likelihood of Hertzian cracking and to increase the probability of fracture initiation at the intaglio surface of the framework. Ninety identical preparations were machined in a dentin-like epoxy composite. Each preparation was restored with a Y-TZP framework made by a CAD/CAM system and veneered using feldspathic ceramic. Prior to cementation the intaglio surface of the ceramic was treated using one of four treatments: 1) cleaning with isopropyl alcohol; 2) application of an overglaze; 3) sandblasting with 125 µm aluminum oxide powder; and 4) sandblasting with 30 µm silica powder (CJ). One of three luting cements were used: 1) zinc phosphate; 2) glass ionomer; and 3) adhesive resin cement (PN). All three cements were tested against frameworks that were alcohol cleaned. Only the PN cements were tested

against frameworks that had been sandblasted or glazed. Altogether, six groups of 15 specimens each were tested. Fatigue resistance was evaluated using stepwise loads at 1.4 Hz until failure: 5000 cycles at maximum load of 200 N, followed by 10,000 cycles at maximum loads of 800, 1000, 1200, and 1400 N. The cement thickness and failure modes were analyzed using a stereomicroscope and scanning electron microscopy. The results were analyzed using the Kaplan-Meier and Mantel-Cox log rank tests (5%), a one-way analysis of variance, Tukey multiple comparison test, and Weibull non-parametric test.

**Results:** The predominant failure mode was chipping of the veneer. The crowns cemented with the adhesive resin cement exhibited chipping failure at higher mean loads than did crowns cemented with cements that usually do not bond strongly with dentin. When the adhesive cement was used, glazing and sandblasting intaglio framework surface treatments exhibited lower mean loads at chipping than did crowns whose intaglio surface was only cleaned with alcohol. Weibull analysis indicated that all specimens had a high ratio of late-to-early failures.

**Conclusions:** The fatigue experiment produced a pattern of failures that is very similar to that observed in clinical trials of Y-TZP crowns that are veneered with feldspathic porcelain. Crowns cemented with an adhesive resin cement exhibited chipping at a significantly higher mean load than those cemented with luting cements that do not usually form strong bonds with dentin. When cemented with adhesive resin cement, glazing or sandblasting the intaglio surface of the framework significantly reduced the mean fatigue loads at which chipping of veneers occurred, as compared to crowns whose intaglio surface had only been cleaned with alcohol. For this cement glazing or sandblasting the intaglio surface of the crown is not recommended.

## INTRODUCTION

The need for more fracture-resistant zirconia has led to the development of tetragonal zirconia polycrystals doped with 3 mol% yttria (3Y-TZP; hereafter this ceramic will be designated Y-TZP). These zirconia-based materials are much more fracture resistant than the feldspathic porcelains traditionally used in dentistry.<sup>1</sup> A major problem with Y-TZP

ceramics is that when subjected to localized stress or chemical stimuli they can undergo phase transformations that undermine their fracture resistance.<sup>2-4</sup> That said, clinical trials show few fractures of Y-TZP cores. Clinical trials of Y-TZP crowns that have been veneered with feldspathic porcelain show that chipping of the veneer is the primary failure associated with these restorations.<sup>3-21</sup>

At the same time, the loss of retention of Y-TZP crowns (due to a lack of adhesion between the Y-TZP surface and the tooth) was also shown to be a reason for failure.<sup>9,10,14-16</sup> The adhesion between the Y-TZP surface and cements has been widely studied in *in vitro* research. Sandblasting, silica coating, etching, and glazing are the most commonly used pretreatments. Silica coating by sandblasting improves adhesion between Y-TZP and resin cement<sup>4</sup>; however, it seems to lead to material degradation. The initially present microdefects introduced by the sandblasting seem insufficient to lead to failure. However, the mechanical strength of the ceramic is time dependent as a result of a subcritical crack growth that the material may suffer when subjected to cyclic loading in an aqueous environment.<sup>22</sup> Indeed, aging of the sandblasted Y-TZP has a deleterious effect on the materials' strength.<sup>23-30</sup> The same is observed for a silica or aluminum oxide coated with silica (SiO<sub>2</sub>) coating.<sup>23,31,32</sup> Contradicting this theory, studies by Cattani-Lorente and others<sup>33</sup> and Scherrer and others<sup>34</sup> cited that sandblasting with 30- $\mu$ m silica particles does not promote a deleterious effect on the mechanical behavior of Y-TZP ceramics. In addition to these surface treatments, surface alterations using Y-TZP ceramic with glazing and etching have been tried. Promising results related to the bond strength between Y-TZP and resin cement were observed with glazed and Al<sub>2</sub>O<sub>3</sub>-sandblasted<sup>35,36</sup> or hydrofluoric acid-etched surfaces.<sup>27,37</sup> However, such a thin glass film is located on the intaglio surface of crowns, which is the area in which tensile stresses are experienced when a crown is mechanically challenged.<sup>38</sup> The presence of this film may trigger the start of crack propagation, since this glass material has a lower tensile strength.

However, there is a lack of evidence in clinical studies related to these intaglio surface treatments, especially in terms of the long-term behavior of the treated crown. The use of luting agents that typically exhibit little adhesion to dentin and ceramics, such as zinc phosphate and glass ionomer, has been studied clinically,<sup>13-15,17</sup> but there are no clinical data comparing the cementation using

these agents with adhesive resin cement. Despite the fact that the loss of retention of Y-TZP/porcelain crowns does not appear to be the main cause of failure in clinical studies, laboratory investigation has observed that cementation success is related to the strength of the crown.<sup>39</sup> Moreover, increased cement thickness decreases failure loads for ceramic crowns.<sup>39</sup>

Thus, instead of measuring the fatigue resistance of individual parts of the system, for example, the Y-TZP ceramic alone or the bond strength of the veneer porcelain to the Y-TZP, we investigated the fracture resistance of an entire system under cyclic loading. The system was a CAM-formed Y-TZP crown that was veneered with feldspathic porcelain and cemented to simulated dentin. We applied stepwise loads to standardized Y-TZP/feldspathic ceramic crowns. Stepwise loading challenges the ceramic to a fixed number of cycles at each load, in a set of incrementally increasing loads, until a load is found in which fracture occurs during the cyclic loading. This fatigue test has been used previously in dental research to determine the fracture resistance of Class II resin composite restorations with cuspal coverage<sup>40</sup> and to compare the fatigue resistance of ceramic and composite veneers.<sup>41</sup>

The present study was designed with the following objectives in mind: 1) to investigate the influence of treatment of the intaglio surface of feldspathic porcelain veneered Y-TZP crowns on fatigue resistance and 2) to evaluate the effects of different luting systems on the fatigue resistance of the crown and veneer system.

## METHODS AND MATERIALS

The fatigue test used in the present work was adapted from one developed by Kelly and others.<sup>42</sup> The present test used a glass-fiber mesh-filled epoxy composite NEMA class G10 (International Paper, Hampton, SC, USA) to simulate the elastic flexibility of dentin and therefore to produce high stresses along the intaglio surface of the crown. Consistent with the fracture behavior of ceramics that have failed clinically,<sup>38,43,44</sup> this test was designed to increase the probability of fracture initiating from the intaglio surface of the framework. Furthermore, also following the method of Kelly and others,<sup>42</sup> the present design applied the load via a large-diameter indenter that spreads the load widely over the outer surface of the crown. This reduces the chance of fracture initiating at the outer surface (here on the outer surface of the veneer).

The *in vitro* survival rates of Y-TZP/porcelain crowns cemented using different cements and pretreatments were determined by fatiguing the crown under stepwise-increasing loads. Computer-aided machining of the G10 composite dentin analogue material was used to produce 90 identical crown preparations, each 6 mm high with a flat top, 12° of total occlusal convergence, and a 1.2-mm chamfer margin. The design of the specimens was based on the results of a previous simulation using finite element analysis.<sup>45</sup>

After a polyvinylsiloxane impression was made, a digital design of a plaster cast was obtained with the aid of InLab 3.60 software (Sirona Dental Systems, Bensheim, Germany). The InLab Cerec MC XL (Sirona Dental Systems) milled 90 identical frameworks in Y-TZP ceramic (VITA In-Ceram YZ for InLab, Vita Zahnfabrik, Bad Säckingen, Germany). The frameworks were ultrasonically and oven-cycle cleaned and then sintered in a ZYrcomat VITA oven (Vita Zahnfabrik), as recommended by the manufacturer. The 0.7-mm-thick framework was veneered using a feldspathic ceramic (Table 1; VITA VM9 base-dentin, Vita Zahnfabrik) with the stratified technique, simulating a full crown with a flat occlusal surface. Two layers of feldspathic ceramic and their consequent two firings in a vacuum furnace (VACUMAT 6000 M, Vita Zahnfabrik) were performed on each crown. The crowns were polished in a grinding machine under constant cooling. The thickness of the crowns was checked with a digital caliper, ensuring that all the crowns had a 2.0-mm total thickness. All the specimens were cleaned for five minutes in an ultrasonic bath of distilled water, air-dried, and submitted to glaze firing (Programat P100, Ivoclar AG Schaan, Liechtenstein) in order to release any possible residual stresses.

## Surface Treatments

The G10 preparations and crowns were numbered from 1 to 90 and then randomized into six groups (n=15) according to pretreatments and cements using the tool at [www.randomizer.org](http://www.randomizer.org), as follows: PN = without surface treatment, resin cement Panavia F; OG = application of a thin glaze porcelain layer, resin cement Panavia F; AO = 125  $\mu\text{m}$   $\text{Al}_2\text{O}_3$  sandblasting, resin cement Panavia F; CJ = 30  $\mu\text{m}$   $\text{SiO}_2$  sandblasting, resin cement Panavia F; ZP = without surface treatment, zinc phosphate cement; and GI = without surface treatment, glass ionomer cement.

The G10 preparations were etched with 10% hydrofluoric acid (Dentsply, Petropolis/RJ, Brazil)

Table 1: Mean Fracture Load (in N) and Standard Deviation (SD), Together with a 95% Confidence Interval, After Stepwise Loading and Cement Thickness ( $\mu\text{m}$ ) for the Different Groups<sup>a</sup>

	Load, N				Cement Thickness, $\mu\text{m}$
	Mean Fracture Load	SD	95% Confidence Interval		
			Lower Bound	Upper Bound	
PN	1093 <sup>A</sup>	237	973	1213	205 <sup>a</sup>
OG	947 <sup>AB</sup>	177	857	1036	271 <sup>a</sup>
AO	973 <sup>AB</sup>	198	873	1074	250 <sup>a</sup>
CJ	920 <sup>AB</sup>	147	845	995	201 <sup>a</sup>
ZP	867 <sup>B</sup>	123	804	929	473 <sup>b</sup>
GI	867 <sup>B</sup>	180	776	958	226 <sup>a</sup>

Abbreviations: AO, 125  $\mu\text{m}$   $\text{Al}_2\text{O}_3$  sandblasting, resin cement Panavia F; CJ, 30  $\mu\text{m}$   $\text{SiO}_2$  sandblasting, resin cement Panavia F; GI, without surface treatment, glass ionomer cement; OG, application of a thin glaze porcelain layer, resin cement Panavia F; PN, without surface treatment, resin cement Panavia F; ZP, without surface treatment, zinc phosphate cement.  
<sup>a</sup> Same uppercase or lowercase letters indicate no statistically significant difference.

for one minute, washed, and dried. For the groups that were to be cemented with Panavia F resin cement, the ED Primer II A & B (Kuraray, Kurashiki, Okayama, Japan) was applied for 30 seconds and then gently air-dried.

All of the crowns were cleaned with isopropyl alcohol and naturally dried through evaporation of the product.

The crowns from the OG group were treated with the overglaze technique, which corresponds to the application of a single thin layer of a glaze porcelain material (VITA AKZENT Glaze and VITA AKZENT Fluid, both from Vita Zahnfabrik) using a brush on the cementation surface. The crowns were then subjected to the glaze-sintering cycle, according to the manufacturer's instructions, at maximum temperatures below the glass transition temperature of the porcelain veneer. The intaglio surfaces were etched with 10% hydrofluoric acid (Dentsply) for one minute, washed, and air-dried. Subsequently, the intaglio surfaces were silanized with Clearfil SE Bond + Bond Activator (Kuraray).

For the sandblasted groups, the sandblasting was performed using 125  $\mu\text{m}$  aluminum oxide particles (Alublast 125  $\mu\text{m}$ , Elephant Dental B.V., Hoorn, The Netherlands) for the group AO or 30  $\mu\text{m}$  aluminum oxide coated with silicon particles (CoJet Sand, 3M ESPE AG, Seefeld, Germany) for the group CJ. The sandblasting was performed at a 15-mm standardized distance from the device's tip to the crown's

occlusal surface in a circular motion for 30 seconds for the AO group and for 15 seconds for the CJ crowns, with a constant pressure of 3 bars (Rocactor Delta, 3M ESPE AG). Crowns from the CJ group were also silanized with Clearfil SE Bond + Bond Activator (Kuraray).

Cementation with Panavia F (Kuraray), zinc phosphate-based cement (Zinc Cement, SS White, Rio de Janeiro/RJ, Brazil), and glass ionomer cement (GC Fuji I Capsule [GC Corporation, Tokyo, Japan]) was completed according to the manufacturers' respective recommendations. Each crown was seated using a standardized force of 50 N over the course of five to seven minutes. The excess cement was removed using small brushes, and the cement was light-cured (Astralis 10, Ivoclar Vivadent AG) using four 30 seconds exposures (Panavia F only). All specimens were stored in distilled water for at least 24 hours and a maximum period of seven days before conducting the stepwise load experiment.

### Stepwise Load Experiment

The specimens were tested until failure in an adapted fatigue tester (Fatigue Tester, ACTA, The Netherlands) with a 1.4-Hz frequency for 5000 cycles at a minimum load of 5 N and a maximum load of 200 N and 10,000 cycles at a minimum load of 5 N and maximum loads of 800, 1000, 1200, and 1400 N, respectively. The load was applied by a 40-mm-diameter stainless-steel sphere<sup>42</sup> (Figure 1) under distilled water<sup>42</sup> at 25°C. The specimens were checked for cracks and/or failures every 1000 cycles.

### Failure Mode Analysis and Cement Thickness

The failure mode of all the specimens was evaluated for a better results comparison. For this purpose, the samples were initially analyzed with a stereomicroscope for localization of the defect that resulted in the failure. The representative specimens were analyzed under scanning electron microscopy (SEM; XL 20, FEI Company, GG Eindhoven, The Netherlands). Three specimens from each group were cut (Isomet 1000, Buehler, Lake Bluff, IL, USA) in 1-mm-thick slices in order to evaluate the thickness of the cement layer. The central slice of each specimen was evaluated via SEM. The cement thickness was the average of the cement layer in the center of the occlusal surface of each slice.

### Statistical Analysis

The step during which each specimen failed was used for the survival analysis. After plotting the data

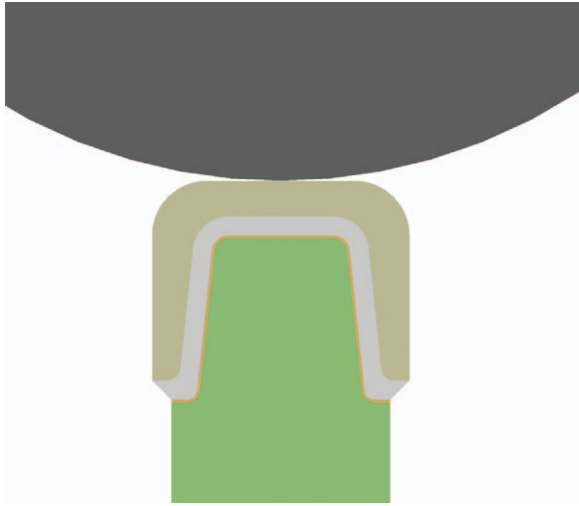


Figure 1. Schematic drawing of the test. Dark gray: 40-mm steel sphere; light brown: porcelain; light gray: YZ infrastructure; orange: cement layer; green: G10 preparation.

in a survival function, the Kaplan-Meier and Mantel-Cox (Log Rank) tests were performed and followed by a pairwise comparison ( $p < 0.05$ ) (SPSS version 21, SPSS Inc, Chicago, IL, USA). The failure steps and total number of cycles to failure were used

for a nonparametric analysis of distribution performed through the two-parameter Weibull analysis using the software Super SMITH Weibull 4.0k-32 (Wes Fulton, Torrance, CA, USA). Data from the occlusal misfit (cement layer) were analyzed by a one-way analysis of variance (ANOVA) and a Tukey test ( $p < 0.05$ ).

## RESULTS

The predominant mode of failure was chipping of the veneer ceramic without exposure of the Y-TZP framework (Figure 2). In six instances the Y-TZP framework fractured: this occurred in one framework for the OG group, two frameworks for the ZP group, and three frameworks for the GI group.

Figure 3 shows the survival curves from the stepwise load experiments for the different groups. The mean fracture loads (in N) calculated from the survival curves and statistical analyses are summarized in Table 1. According to the Mantel-Cox test (Log Rank,  $\chi^2 = 13.422$ ,  $df = 5$ ,  $p = 0.02$ ), consequently, the tested conditions influenced the fatigue resistance of the porcelain veneered Y-TZP crowns. The pairwise comparison showed that the adhesively cemented (PN) crowns survived at significantly

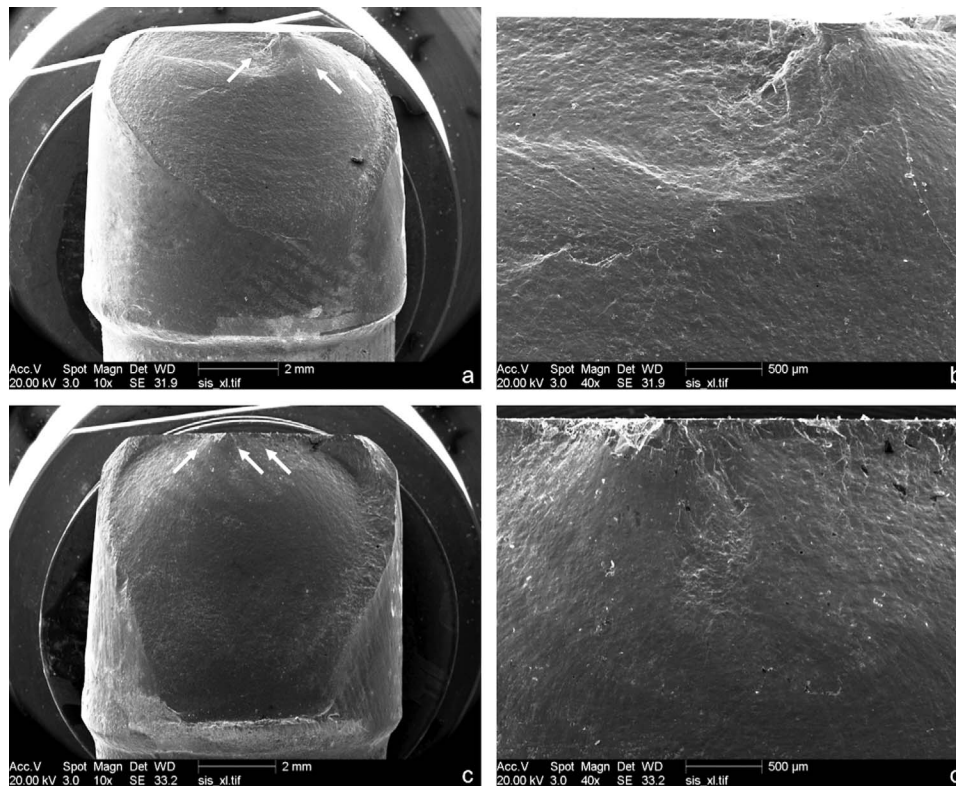


Figure 2. The predominant mode of failure: chipping of the veneer ceramic. Representative images from groups AO (a,b) and CJ (c,d). The white arrows represent the direction of fracture propagation.



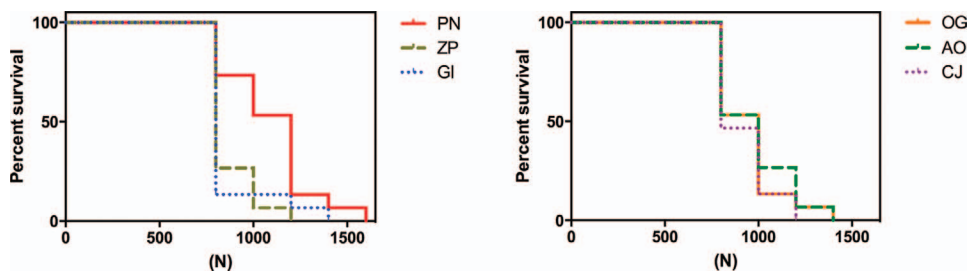


Figure 3. Survival curves of the stepwise load experiment analyzed according to the steps during which each crown failed.

higher loads (and, consequently, for more cycles) than the crowns luted with zinc phosphate (ZP) or glass ionomer cements (GI). For crowns whose intaglio surface had been “treated” (ie, glazed or sandblasted prior to bonding), there were no significant differences ( $p > 0.05$ ) in the fatigue loads (ie, loads at which chipping occurred) of treated crowns luted with the adhesive resin cement and untreated crowns luted with zinc phosphate or glass-ionomer cement (Table 1).

Table 2 and Figure 4 summarize the Weibull statistics of the stepwise load experiment analyzed according to the maximum load (top) or the number of cycles (bottom) at which each veneer chipped.

The cement thickness was also analyzed. A one-way ANOVA showed differences among the cement thicknesses of the experimental groups ( $p < 0.0001$ ). The Tukey test showed that zinc phosphate had the

thickest layer compared to all the other groups (Figure 5; Table 1).

### DISCUSSION

The failure mode of the majority of specimens during the stepwise load experiment was cohesive failure of the porcelain (eg, chipping) without exposure of Y-TZP. The results of the Kaplan-Meier survival analysis showed statistically significant differences among the experimental groups. The stepwise load experiments showed that the crowns cemented with the adhesive resin cement failed at higher loads than did the crowns cemented with the luting cements that usually exhibit little adhesion to dentin and ceramics.

Zinc phosphate cement has been used for more than a century in dentistry.<sup>46</sup> Despite its low mechanical strength, lack of a chemical bond, and partial solubility to oral fluids, this cement has been

Table 2: Weibull Parameters, Correlation Coefficients, and the 5% Failure Value (B5%) with their 95% Confidence Interval After Analyzing Stepwise Loading, Depending on the Load-to-Failure (N) and the Total Number of Cycles to Failure

	Weibull—Load to Failure					
	$\sigma_0$	$\beta$	$r^2$	95% Lower	B5%	95% Higher
PN	1175	5.699	0.858	570	698	855
OG	997	8.039	0.678	607	689	783
AO	1033	6.949	0.723	572	673	793
CJ	964	9.217	0.660	618	699	790
ZP	895	13.11	0.455	666	714	765
GI	890	12.61	0.280	661	703	749
	Weibull—Number of Cycles					
	$N_{i,0}$	m	$r^2$	95% Lower	B5%	95% Higher
PN	26,306	2.023	0.969	3312	6059	11,084
OG	16,895	1.896	0.910	1886	3528	6601
AO	21,204	2.138	0.961	3004	5286	9301
CJ	18,069	2.316	0.922	2933	5011	8563
ZP	13,649	2.574	0.887	2801	4305	6619
GI	12,078	2.267	0.723	2042	3258	5198

Abbreviations: AO, 125  $\mu\text{m}$   $\text{Al}_2\text{O}_3$  sandblasting, resin cement Panavia F; CJ, 30  $\mu\text{m}$   $\text{SiO}_2$  sandblasting, resin cement Panavia F; GI, without surface treatment, glass ionomer cement; OG, application of a thin glaze porcelain layer, resin cement Panavia F; PN, without surface treatment, resin cement Panavia F; ZP, without surface treatment, zinc phosphate cement.

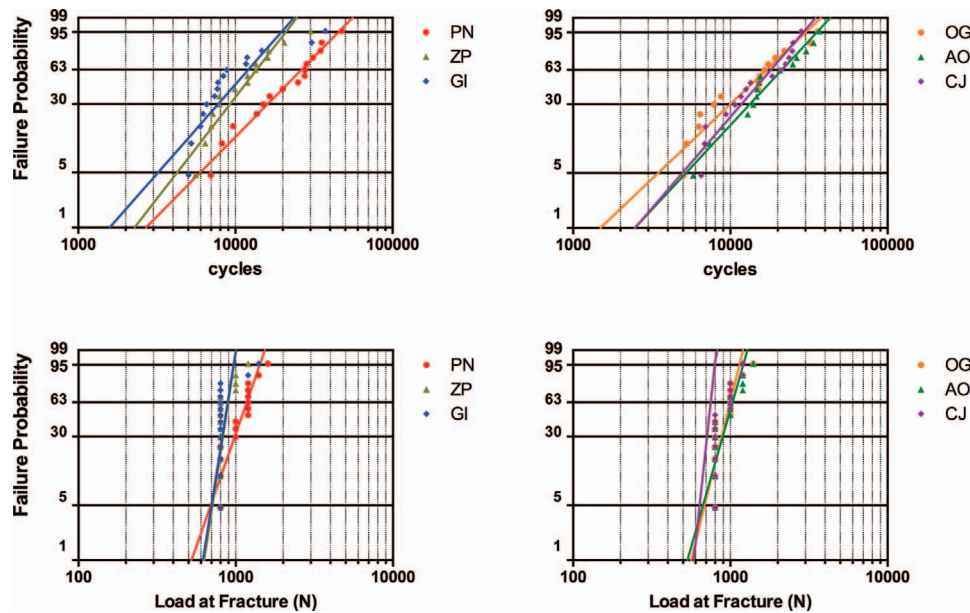


Figure 4. Weibull probability plots of the stepwise load experiment analyzed based on the number of steps or cycles during which each crown failed.

used by several other authors.<sup>14,46-50</sup> Both resin cement and glass ionomer cement have better mechanical properties than does zinc phosphate. The superior strength of resin cements may contribute to better bond strength between computer-aided machined zirconia copings and a nickel-chromium (Ni-Cr) alloy<sup>50</sup> and better retention of zirconia crowns to dentin.<sup>51</sup> Notably, the bond strength of resin cement to dentin is greater than that of zinc phosphate or glass ionomer cements to dentin.<sup>50</sup>

Although the bond strength of the adhesive resin cement to the epoxy composite (G10) used in the present experiments was found to be similar to that of the adhesive resin cement bonded to wet

dentin,<sup>42</sup> the bond strengths of zinc phosphate cement and glass ionomer cement to the epoxy resin composite have not been measured. It is known that fracture resistance (monolithic test) of feldspathic monolithic crowns can be influenced by their adhesion mechanism to resin cement.<sup>39</sup> A feldspathic crown “bonded” to cement resisted twice the load of “nonbonded” crowns.<sup>39</sup> Apparently, the present work is the first one to observe the influence of luting agents on the fatigue resistance of Y-TZP crowns veneered by porcelain. Consequently, it is not known whether the present results can be extrapolated to Y-TZP bonded to dentin with zinc phosphate or glass ionomer cements. Further studies should be addressed in order to better explore this topic.

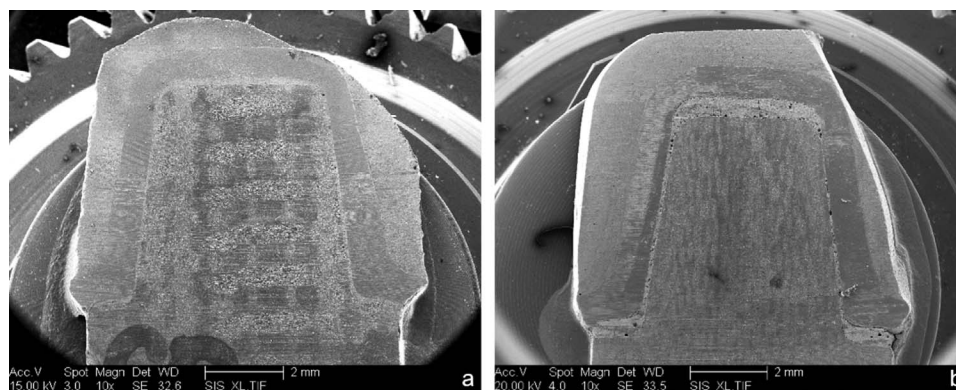


Figure 5. Representative images of cement thickness from groups PN (a) and ZP (b).



Results similar to those in the present study have been reported for a study<sup>50</sup> of the fracture resistance of zirconia copings. Namely, when standard copings were luted to a Ni-Cr alloy, lower fracture resistance was found for copings luted with zinc phosphate or glass ionomer cements, and much higher fracture resistances were found for copings luted with an adhesive resin cement.<sup>50</sup>

In this study, the Kaplan-Meier analysis showed that Y-TZP crowns luted with the adhesive resin cement whose intaglio surface had been “treated” (eg, glazed or sandblasted) exhibited veneer failures at fatigue loads that were not significantly different ( $p > 0.05$ ) from those exhibited by untreated crowns that had been luted with cements that usually do not form strong bonds to dentin. Sandblasting the intaglio surfaces of Y-TZP frameworks is controversial.<sup>2,19</sup> Very different surfaces can be produced by varying the types and sizes of particles, pressures, area of the jet of sand and projection angle and by using target materials with varying microstructures.<sup>52</sup>

After fatigue, Y-TZP specimens that have been sandblasted with aluminum oxide using parameters similar to those used in the present study exhibit reduced strength.<sup>23,29,30</sup> The same deleterious effect is observed in zirconia that has been sandblasted with silica.<sup>23,31,32</sup> Studies related to the application of overglaze suggest that this treatment is advantageous to the ceramic system as a whole.<sup>27,28,35,37,53-56</sup> Nevertheless, in the present study, the fatigue resistances of the treated Y-TZP crowns (AO: sandblasting with 125  $\mu\text{m}$   $\text{Al}_2\text{O}_3$ ; CJ: sandblasting with 30  $\mu\text{m}$   $\text{SiO}_2$ ; and OG: application of overglaze) were not significantly different from those of the untreated crowns (PN).

The fatigue behavior of dental materials is generally investigated by a high number of cycles at a low load or by staircase fatigue experiments. A new approach was introduced by Fennis and others,<sup>40</sup> in whose study a stepwise load was applied and resistance to survival was analyzed using log-rank tests. In order to understand the failure mechanism, we analyzed the results with a traditional Weibull analysis using the failure criteria “load to failure” and the “number of cycles to failure.” There was a clear difference in the results: for the “load to failure,” the Weibull correlation coefficient was between 0.85 and 0.28, while the correlation coefficient of the “number of cycles to failure” was 0.97 to 0.72. The high correlation coefficient of the “number of cycles to failure” showed that the failure mechanism is most likely related to slow crack

growth instead of the probability of overload, which is expected for a high correlation with the “load to failure.” The Weibull analysis for the “number of cycles to failure” showed values of  $m > 1$ , which means that most of the failures occurred relatively late.<sup>57</sup>

Interestingly, the  $m$  value of the investigated groups was similar ( $m=1.9-2.5$ ), showing that the physics of the failure were similar for all groups. This means that the observed failure mode (eg, delamination of the veneer porcelain) for investigated specimens had the same origin. Recently, Carvalho and others<sup>58</sup> investigated the fatigue resistance of feldspathic glass ceramics, lithium disilicate, and resin nanoceramic crowns in a similar setup. The mean fracture strength of their feldspathic glass ceramics (Vitablocs Mark II blocks) was 1171 N, which is similar to our mean fracture strength. This implies that the strength of the veneer porcelain, or the bond strength between the veneer porcelain and the Y-TZP, is determining the overall fatigue resistance. A closer look at the failure mode analysis showed that the majority of specimens had porcelain cohesive failure (chipping) without exposure to Y-TZP, which corroborates with clinical<sup>3,5-21</sup> and laboratory studies.<sup>58-61</sup>

Although this experiment was designed to test the effect of the surface treatments prior to cementation on the fatigue resistance of Y-TZP infrastructure/porcelain veneer crowns, there were few failures of the Y-TZP framework (six crowns, or 6.67%). This fatigue test produced approximately the same percentage of framework failures as has been seen in clinical trials of Y-TZP crowns. For example, three clinical trials, those of Schmitter and others,<sup>16</sup> Çehreli and others,<sup>62</sup> and Beuer and others,<sup>63</sup> reported 3%, 7%, and 5% framework fractures, respectively. Clinically similar fracture is best simulated by cementing to a preparation with dentin-like elastic properties and avoiding high surface stresses with use of a large-diameter applicator,<sup>42</sup> unlike that used in some recent studies.<sup>60,64</sup>

The thickness of the cement layer was also evaluated. Only the ZP group was significantly thicker than the other groups. This is most likely due to the composition of this cement. According to Jorgensen,<sup>65</sup> the particles of the zinc phosphate powder are only partially dissolved by the acid contained in the liquid, resulting in agglomerated particle formation of up to 100  $\mu\text{m}$ . These clusters can hinder the spread of the cement in the space between the crown and preparation, thereby damaging the adaptation. Despite the differences found

between the thicknesses of the cements that usually do not form strong bonds to dentin, the behavior of the specimens cemented with both cements was similar in the fatigue-resistance test, reinforcing the notion that the modulus of elasticity of the cement has more influence on stress formation in the ceramics and in its interface with cement than does the thickness of the cement layer itself.<sup>66</sup> According to Shahrabaf and others,<sup>67</sup> an increase in the elastic modulus of the cement leads to higher stresses in the cement layer for crowns with flat preparations. In this case, the resin cement (elastic modulus of 3 GPa; Yi and Kelly<sup>68</sup>) better distributes the stresses within this layer than do the glass ionomer cements (between 6.3 GPa [Tam and others<sup>69</sup>] and 16.9 GPa [Li and White<sup>70</sup>]) or the zinc phosphate cement (between 13.7 GPa [Craig and others<sup>71</sup>] and 22.4 GPa [Holmes and others<sup>72</sup>]). For crowns with untreated intaglio surfaces, the low modulus of the resin cement may explain the superior fatigue resistances exhibited by crowns cemented with this cement over crowns cemented with zinc phosphate or glass ionomer cements.

In addition to the unknown amounts of adhesion between the dentin analogue and the GI or the ZP luting cements, the main limitations of this study were the brief times in water and the 12° convergence angle of the preparation. The relatively brief storage times in water (between one and seven days) are insufficient to produce the losses in bond strength that have been reported for bonds between Y-TZP and an MDP (10-Methacryloyloxydecyl dihydrogen phosphate)-containing adhesive resin cement. In clinical situations, the water uptake might be slower as a result of the different configurations, but water will eventually reduce the bond strength<sup>73</sup> and most likely the resistance of the survival of the crown. Lower convergence angles of the preparation can be associated with the occurrence of Hoop stresses within the restoration and the reduced resistance of the crown when it is loaded.<sup>74</sup> Finite element analysis is needed to show where these stress concentrations are and what their effects are in terms of the lifetime of the crown.

### CONCLUSIONS

The experimental fatigue model that was used produced failures similar to those that are observed *in vivo*. The zirconia frameworks rarely failed, but veneers frequently fractured cohesively. Paradoxically, the experimental model was designed to produce framework fractures that initiate in the inside of the framework near the cement and to

minimize surface stresses that could lead to Hertzian fracture at the surface. This experimental model is an excellent candidate for *in vitro* studies of veneered ceramic.

When the intaglio surfaces of crowns were untreated, crowns luted with the adhesive resin cement exhibited veneer failure at higher loads than did those cemented with either the zinc phosphate or glass ionomer luting cements. Furthermore, pretreatments, such as overglazing, sandblasting, or silica coating, did not affect failure load. The Weibull analysis showed that the number of cycles in the stepwise load experiments is related to a failure mechanism that includes slow crack growth.

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### Regulatory Statement

This study was conducted in accordance with all the provisions and policies of the Institute of Science and Technology, University Estadual Paulista in Sao Jose dos Campos in Sao Paulo, Brazil.

### Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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