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RESEARCH AND EDUCATION

Assessment of the survival and success rates of lithium disilicate crowns after different surface finishing procedures: An in vitro study

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ABSTRACT

Statement of problem. Evidence is limited for the impact of clinical adjustments and polishing on the longevity of glazed lithium disilicate restorations.

Purpose. The purpose of this in vitro study was to evaluate the influence of surface finishing on the survival and success rates of lithium disilicate restorations based on fatigue resistance and failure mode.

Material and methods. Lithium disilicate (IPS e.max CAD) maxillary premolar crowns (N=54) were cemented on a dentin analog. The restorations were divided into 3 groups: overglaze (OG), abrasion (GA), and abrasion and polishing (AP). The crowns were submitted to cyclic fatigue in 37 °C water at 100 N and 2 Hz in 2 lifetimes. The load was applied to the occlusal surface by using anatomic pistons to simulate a clinical tripod occlusal contact. After cycling, the crowns were examined for failure (cracking, chipping, or catastrophic fractures) under optical and scanning electron microscopy. Cracking was considered either a structural failure (success analysis) or a survival (clinical criteria - survival analysis). Data were analyzed by using the log rank Kaplan-Meier and Holm-Sidak tests (α=.05).

Results. Surface finishing had no influence on the structural integrity of lithium disilicate, with similar success rates (P=.720). The calculated survival rate was higher for AP than that for other groups (P=.028). Cracking was found for GA and AP crowns, mostly initiating from the external surface. Chipping occurred in all experimental groups, and AP crowns did not show catastrophic failures.

Conclusions. Although surface treatments had no influence on the success of lithium disilicate, polishing showed a positive effect on the survival rate of the crowns based on the clinical implications of cracking (no need for replacement). (J Prosthet Dent 2023;129:897-905)

The success, survival, and failure of ceramic restorations have been defined by clinical criteria.[1,2] A restoration is classified as a success when it shows no structural or clinical complications and as survival when the observed complications do not require a replacement, while failure implies any unacceptable condition (surface quality, anatomic contour, function, or esthetics) leading to the replacement of the restoration.[1-3] Clinical trials and systematic reviews have used these parameters to report the success and survival rates of ceramic restorations.[4-7]

For lithium disilicate glass-ceramic restorations, clinical studies have reported a survival rate of 89.7% to 97.7% after 5 years[4-6] and 83.5% to 96.5% after 10 years [5-7] The structural problems reported for lithium disilicate glass-ceramic crowns include cracking, chipping, and catastrophic fractures.[2,4-7] These studies often considered cracking as a survival, while chipping and catastrophic failures have been considered failures.

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Clinical Implications

The longevity of restorations can be assessed based on a material's structural integrity (success analysis) or on the clinical criteria for replacement (survival rates), which report only restorations in an unacceptable condition for clinical service as "failures." The present study demonstrated that lithium disilicate crowns' surface should be polished to increase their survival rate.

From a clinical perspective, the presence of cracks in a glass-ceramic restoration typically does not compromise esthetics or function and is associated with the survival rate in clinical studies.[1,2] However, once a crack has been nucleated, it can propagate to a critical size (especially under fatigue in the wet oral environment), originating fragment(s) and compromising the structural integrity. In this situation, cracking is often considered a restoration failure and has been associated with the success rate in in vitro studies.[8-14] When discussing the clinical significance of in vitro studies, the clinical criteria used for failure classification usually report "repairable or irreparable fractures" to account for restoration survival or failure.[1,4,15,16]

Fabrication and clinical aspects can be related to the nucleation and propagation of cracks in lithium disilicate glass-ceramic restorations.[17-19] After crystallization, a layer of low-fusion glass (overglaze) is often applied to the restorations to provide a smooth external surface, to adjust color, and to improve esthetics.[4,9,20,21] In addition, the overglaze could seal microcracks or porosity and increase the mechanical performance of the glass-ceramic.[20-22]

In clinical practice, ceramic restorations often require recontouring and adjustments.[21,23] These procedures are typically performed by using diamond rotary instruments, resulting in a rougher surface, reducing the optical properties (reflectance) and the overall esthetics, and increasing surface defects that can reduce fracture strength.[20,21,23] Therefore, surface polishing is important to reduce surface irregularities.[21,22] Nevertheless, it has been reported that the resulting surface roughness after overglaze, abrasion by using diamond rotary instruments, or polishing has no influence on the catastrophic fracture of lithium disilicate crowns under monotonic loading.[21] However, finishing and polishing protocols can introduce surface defects from which cracks can propagate under cyclic contact fatigue, resulting in cracking, chipping, or catastrophic failures (clinical failures reported in the literature).[4-7] Fractures can originate at the ceramic-cement interface adjacent to the loading site,[24,25] at the occlusal contact area with axial loading or sliding (cone cracks),[26] or at areas of structural deficiencies (reduced wall thickness) such as the cervical region.[16,24,27-31]

Discrepancies between intraoral conditions and in vitro tests have been reported.[13,29,31-34] Clinical fractures occur under cyclic loads ranging from 5 N to 364 N in a masticatory frequency of 1 to 2 Hz,[11,24,31,32] and they often result in only 2 or 3 fragments. In in vitro monotonic tests, the combination of high fracture loads (above the maximum occlusal forces reported clinically) and a reduced loading area on the restoration surface often results in fracture with multiple fragments.[29,30,34] This mode of fracture could be compared with a random impact or an occasional higher occlusal force, rather than the normal masticatory cycle.[30,33] Mechanical cycling under water by using loads with the magnitude range of normal occlusal forces promotes slow crack growth and cyclic fatigue mechanisms that can degrade the mechanical properties of ceramics, as observed in the clinical condition.[11,24,25,32,34,35] As the loading area can have a significant influence on the restoration's mechanical behavior and mode of failure,[25,29] it is important to develop a loading configuration similar to that of the clinical occlusal contact.[1,29]

Therefore, the objective of this in vitro study was to evaluate the influence of surface finishing (overglaze, abrasion, and polishing) on the survival and success rates based on the fatigue resistance and failure mode of lithium disilicate glass-ceramic crowns, testing the hypothesis that the surface finishing would influence the crown resistance under fatigue. In addition, this study considered the fatigue analysis reporting cracking as survival rate (clinical perspective) or as success rate (structural integrity perspective), testing the null hypothesis that the calculated survival and success rates would be similar among the studied groups. Also, the study analyzed the failure modes, testing the null hypothesis that the failure modes would not be associated with the type of surface finish.

MATERIAL AND METHODS

Table 1 presents the materials used in the study. Rods (Ø20×1200 mm) of a dentin analog material (NEMA G10; International Paper) were milled to simulate simplified preparations for maxillary second premolar crowns (N= 54).[21] A 1.2-mm-wide cervical chamfer finish line was used, and the angles between the axial and occlusal walls were rounded.

A preparation was scanned to standardize the internal fit of the crowns, and a cement space line of 100 μm was provided. Lithium disilicate (IPS e.max CAD; Ivoclar AG) blocks were milled in a computer-aided design and

Table 1. Description of materials used

Material	Commercial Name	Manufacturer	Description*
Dentin analog	NEMA G10	International Paper	Glass fiber reinforced epoxy resin
Glass-ceramic	IPS e.max CAD	Ivoclar AG	SiO_2 (57- 80%), Li_2O (11%-19%), K_2O (0-13%), P_2O_5 (0%-11%), ZrO_2 (0%-8%), ZnO (0%-8%)
Hydrofluoric acid	Condac Porcelana	FGM	Hydrofluoric acid (10%)
Silane	Monobond S	Ivoclar AG	Methacryloxypropyltrimethoxysilane (1%), ethyl alcohol (52%), distilled water (47%)
Resin cement	Multilink N	Ivoclar AG	Self-adhesive luting agent Base: dimethacrylate and HEMA (30.5%); barium glass and silicon dioxide fillers (45.5%); ytterbium trifluoride (23.0%); catalysts and stabilizers (1.0%); pigments (<0.01%) Catalyst: dimethacrylate and HEMA (30.2%); barium glass and silicon dioxide fillers (45.5%); ytterbium trifluoride (23.0%); catalysts and stabilizers (1.3%); pigments (<0.01%)
Overglaze	IPS e.max CAD Crystall/Glaze	Ivoclar AG	Low-fusion glass
Diamond rotatory instruments	#2135FF	KG Sorensen	Extra-fine tungsten diamond rotatory instruments (30 μm)
Polishing finishers	OptraFine	Ivoclar AG	Silicone finishers with diamond particles
High polishing nylon brush	OptraFine	Ivoclar AG	Synthetic nylon fiber brushes
Polishing paste	OptraFine HP	Ivoclar AG	Diamond paste for high-gloss polishing

*Information from manufacturers.

computer-aided manufacturing (CAD-CAM) system (InLab MCX5; Dentsply Sirona) by following the second maxillary premolar natural design (Software InLab 19; Dentsply Sirona) with main grooves and cusps (Fig. 1). The milled crowns were submitted to a crystallization firing cycle (Programat P310; Ivoclar AG).[13] After crystallization, a thin layer of overglaze (IPS e.max CAD Crystall/Glaze; Ivoclar AG) was applied to the external surface of all crowns with a brush and were sintered according to the manufacturer's instructions.

The 3D model file of a ceramic crown was used to design a piston that fit to the occlusal surface. The dentin analog rods (NEMA G-10; International Paper) were milled to obtain 54 pistons. The fit of the pistons to the premolar occlusal surface was tested to ensure simultaneous 3-point occlusal contacts as shown in Figure 2. The preparations were stored in distilled water at 37 °C for 2 weeks before cementation.[30,36] All crowns were tested for fit on the preparations before the cementation procedure; no adjustments were required.

The crowns were cleaned in an ultrasonic bath (Ultrasound Tubes Instrument; Cristofoli Ltda) with alcohol for 5 minutes and distilled water for 5 minutes. The bonding surfaces of the preparations and crowns were etched with 10% hydrofluoric acid (Condac Porcelain; FGM Dental Group) for 20 seconds. The acid was removed by using an air-water spray for 40 seconds, followed by an ultrasonic bath in distilled water for 5 minutes. After air-drying for 30 seconds, a drop of silane (Ivoclar AG) was applied to the etched surfaces with a disposable microbrush (KG Brush; KG Sorensen) and allowed to evaporate for 3 minutes. A self-adhesive resin cement (Multilink N; Ivoclar AG) was applied on the treated intaglio surface of the crowns with automix tips. The crowns were fully seated on the preparations under finger pressure, a load of 7.35 N was applied to the occlusal surface for 5 minutes, and the excess cement was removed with a microbrush. Finally, the resin cement was light-activated with a 1500-mW/cm^2 light-polymerization unit (Radii Plus; SDI) for 10 seconds on each side and 20 seconds on the occlusal surface (100 seconds of total light activation).

The cemented crowns were divided into 3 experimental groups according to the occlusal surface finish procedures: overglazed (OG-control), abrasion with extrafine diamond rotary instruments (GA), and abrasion with extrafine diamond rotatory instruments and polish with polishing finishers and diamond paste (OptraFine; Ivoclar AG). A pilot study compared the abrasion and polishing procedures performed manually with the same procedures performed with the assistance of a mechanical device. The manual abrasion and polishing procedures performed by a trained operator resulted in more homogeneous and consistent surfaces than those with the mechanical device, which was mostly because of the inherent challenge offered by the occlusal anatomy. Therefore, such procedures were performed by a single experienced dentist (L.S.R.) by using controlled air pressure to avoid excess material removal and differences in ceramic thickness, which was evaluated with digital calipers (Digimatic Absolute 500-136-20b; Mitutoyo).

The occlusal abrasion was performed with extrafine diamond rotary instruments (changed every 5 specimens) mounted on a high-speed handpiece with 170 000 to 180 000 rpm and under water cooling for 2 minutes. Surface polishing was performed by using a polishing system (OptraFine; Ivoclar AG) with the silicone finishers

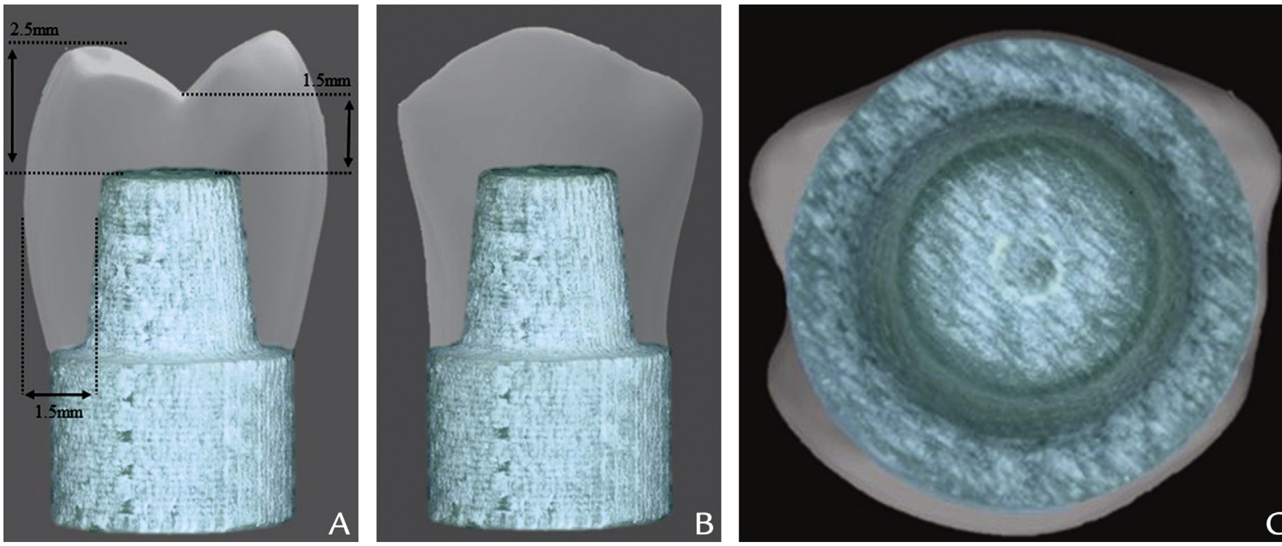

Figure 1. Glass-ceramic crown and preparation design on different areas of restoration. A, Proximal view. B, Buccal view. C, Occlusal view.

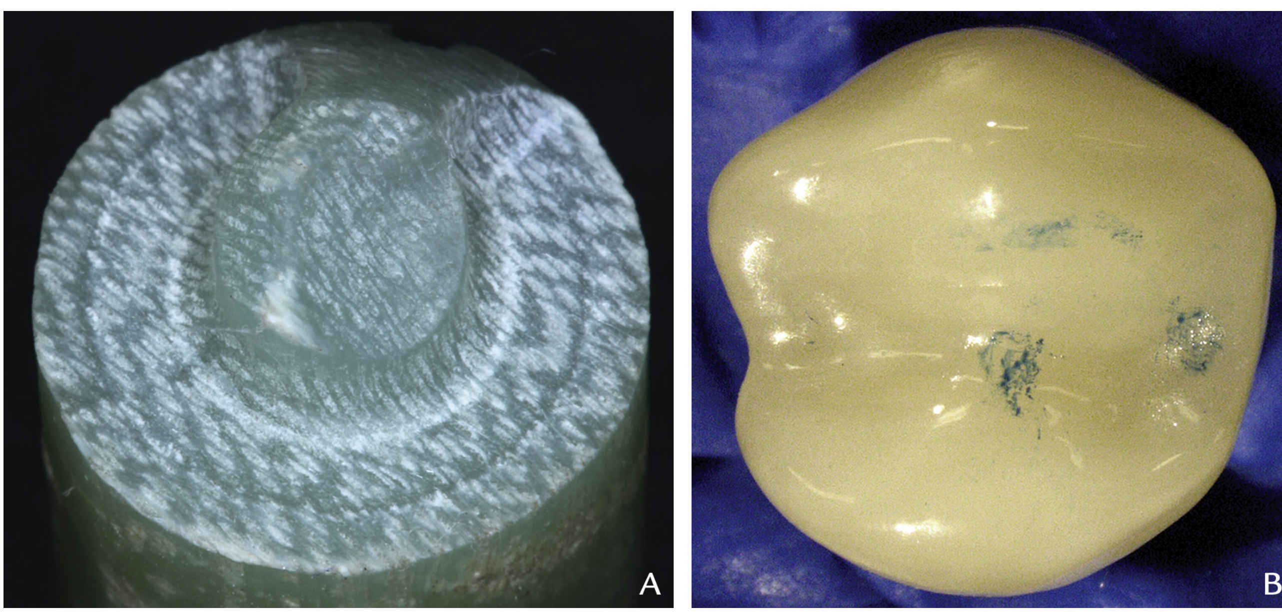

Figure 2. A, Loading piston fit to premolar crown occlusal surface. B, Occlusal surface marks (tripod contact) from piston loading on ceramic crown.

and polishing paste recommended by the ceramic manufacturer in a low-speed handpiece with 40 000 to 50 000 rpm for 2 minutes.

The specimens were stored in distilled water at 37 °C before mechanical cycling. The fatigue test was performed in a pneumatic mechanical cycling machine (Biocycle V1; Biopdi) for 2 lifetimes: 1×10^6 and 2×10^6 cycles with a frequency of 2 Hz in distilled water at 37 °C. The anatomic piston applied a load of 100 N to the occlusal surface of the crown. The tripod contact was evaluated by using articulating paper (Articulating Paper 40 μm; Bausch) (Fig. 2B). Each crown was loaded by a new piston (Fig. 2A).

All specimens were examined by using transillumination with blue light (the light-polymerizing unit) to identify cracks and other fractographic features at the end of each cycling time. Fractured crowns were cleaned in an ultrasonic water bath and dried with oil-free air spray. The fractured surfaces were gold-coated and examined under optical microscopy and scanning electron microscopy (Vega 3 LM; Tescan Analytics). The fracture origins were identified by using fractographic principles.[24,26] Failures were classified as cracking, chipping (fracture with no exposure of cementation surface), or catastrophic fracture (exposing the cementation surface). The origins of the catastrophic failures were

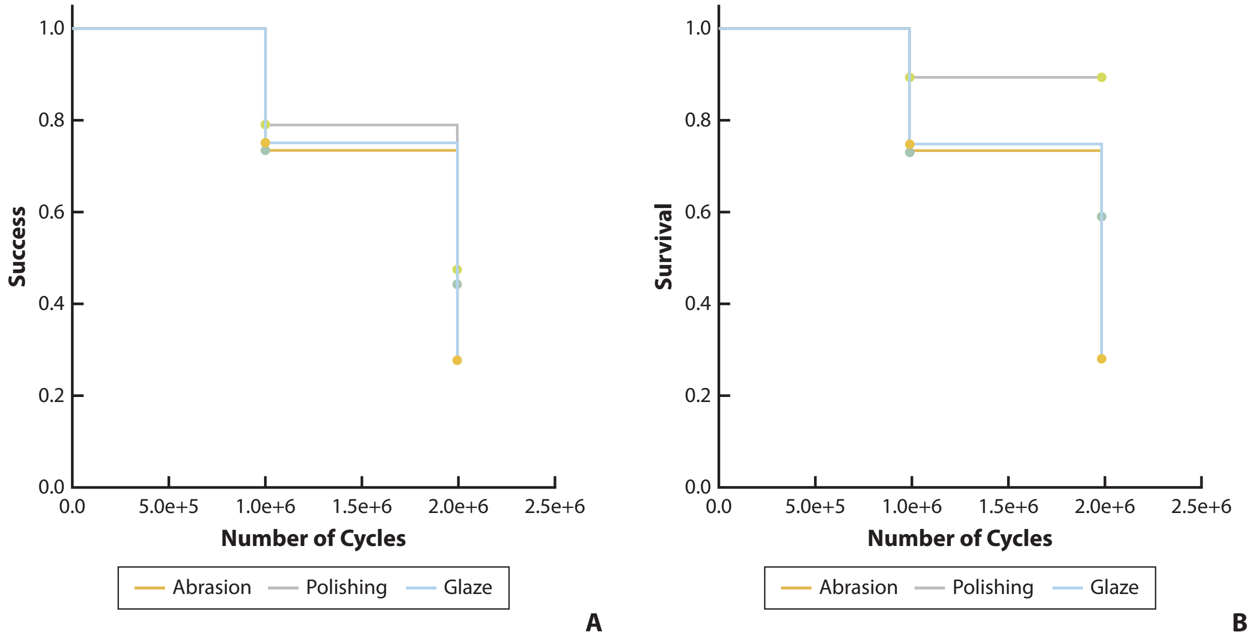

Figure 3. Kaplan-Meier curves. A, For success analysis (considering cracks as structural integrity failures). No significant difference among groups (P=.720). B, Survival analysis (considering cracking as survival). AP (polishing) showed higher survival than GA and OG (P=.028).

Table 2. Mode of failure and success-survival data for each experimental group based on lifetime (number of cycles)

				Success Analysis	Survival Analysis	Failure Mode (n)				
								Catastrophic		
Experimental Group	Lifetime (Cycles)	Tested Sample (n)	No Failure (n, %)	Failures (n, %)	Failures (n, %)	Cracking*	Chipping	Intaglio	Combined	Occlusal Surface
OG	1×10^6	8	4 (50)	4 (50)	4 (50)	-	2	-	2	-
	2×10^6	8	3 (38)	5 (62)	5 (62)	-	3	1	1	-
GA	1×10^6	9	4 (44)	5 (56)	5 (56)	-	4	-	-	1
	2×10^6	10	6 (60)	4 (40)	2 (20)	2	2	-	-	-
AP	1×10^6	9	5 (56)	4 (44)	2 (22)	2	2	-	-	-
	2×10^6	10	6 (60)	4 (40)	0 (0)	4	-	-	-	-

*Radial cracks originated in intaglio surface of restorations near load application area.

identified and classified as ceramic-cement interface, external surface, or events combining both origins.

Cracks were considered a structural failure for the success analysis and survival for the survival analysis, based on clinical criteria for restoration replacement.[1] Kaplan-Meier survival and success curves were obtained and compared by using the Holm-Sidak test. A descriptive failure analysis was performed. Failure modes were compared by using the Fisher Exact test (α=.05).

RESULTS

For the success analysis, the failure rate (Fig. 3A) was calculated according to the number of cycles (Table 2). No significant difference in the success rate of the restorations was found among the experimental groups (P=.720). The average success for OG was 1 750 000 cycles; for GA, 1 736 842 cycles; and for AP, 1 789 473 cycles.

The failure rate (Fig. 3B) was calculated according to the number of cycles for the survival analysis (Table 2). The presence of cracks was considered as a restoration survival. Polishing treatment showed the highest survival rate compared with overglaze and abrasion (P=.028). The average survival times were 1 750 000 cycles for OG, 1 736 842 for GA, and 1 894 736 for AP.

The mode of failure was influenced by the finishing procedures (Table 2). Representative images of the modes of failure are shown in Figure 4. Chipping was observed for all experimental groups, initiating at the surface or subsurface, as shown in Figure 5. A higher number of catastrophic failures (P=.005), mostly originated at the intaglio surface, and chipping (P=.021) initiating at the external surface were found in the OG group than those in the AP group. Chipping was the most frequent mode of failure for GA, initiating at the surface near the occlusal contact, usually in the thinnest

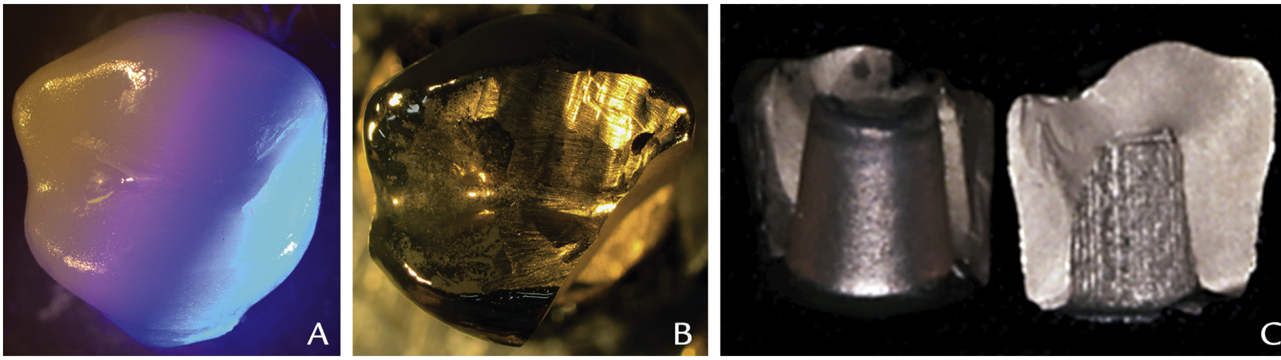

Figure 4. Representative images of failure modes. A, Cracking (AP crown). B, Chipping (GA crown). C, Catastrophic fracture (OG crown). Original magnification ×60.

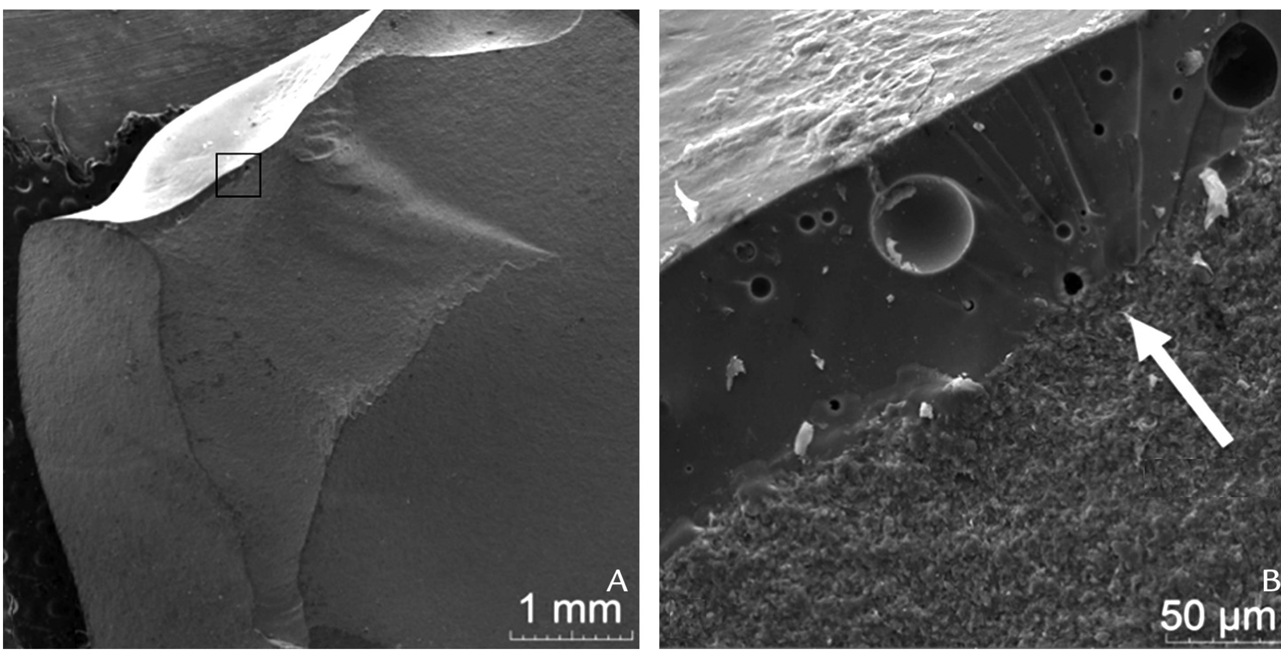

Figure 5. Representative scanning electron micrographs showing failure origin. A, Chipping failure with crack origin at overglaze-ceramic interface near load application area (OG group, lifetime of 1×10^6 cycles). Original magnification ×200. B, Fracture origin (*white arrow*) identified by using characteristic fractographic marks. Original magnification ×1000.

ceramic area (Figs. 6, 7). Most AP failures were ceramic cracking (radial cracks initiating at the interface).

DISCUSSION

The present study showed the influence of surface finishing procedures (overglaze, abrasion, and polishing) on the survival of lithium disilicate glass-ceramic restorations, which depended on how "failure" was determined.[1,2] Cracks compromise the structural integrity of the ceramic and can be considered as "failure" in a success analysis. In this situation, no influence of different surface finishing was found on the crown resistance under fatigue, supporting the null hypothesis. However, considering the clinical implications of the presence of cracks on a restoration in service (no need for replacement), crowns with cracks can be classified as "survival." In this situation, the polishing protocol showed a positive effect on the survival of the crowns compared with the other groups, rejecting the null hypothesis. Therefore, as the present study found a difference in the calculated survival rates for the survival and success analyses, the second null hypothesis was rejected.

Abrasion with diamond rotary instruments can produce defects from which cracks can initiate and propagate until catastrophic failure of the restoration. Extrafine diamond rotary instruments (average grit size of 30 μm) were used to abrade the surface, simulating the clinical

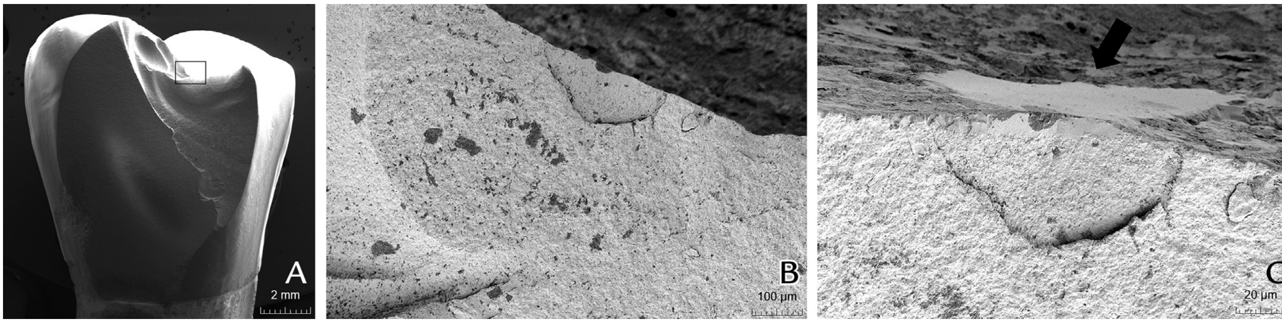

Figure 6. Representative scanning electron micrographs showing failure origin. A, B, Chipping failure with critical crack at occlusal surface (GA group, lifetime of 1×10^6 cycles). C, Failure occurred at contact area with piston (*black arrow*). Original magnification: A, ×50, B, ×400, C, ×800.

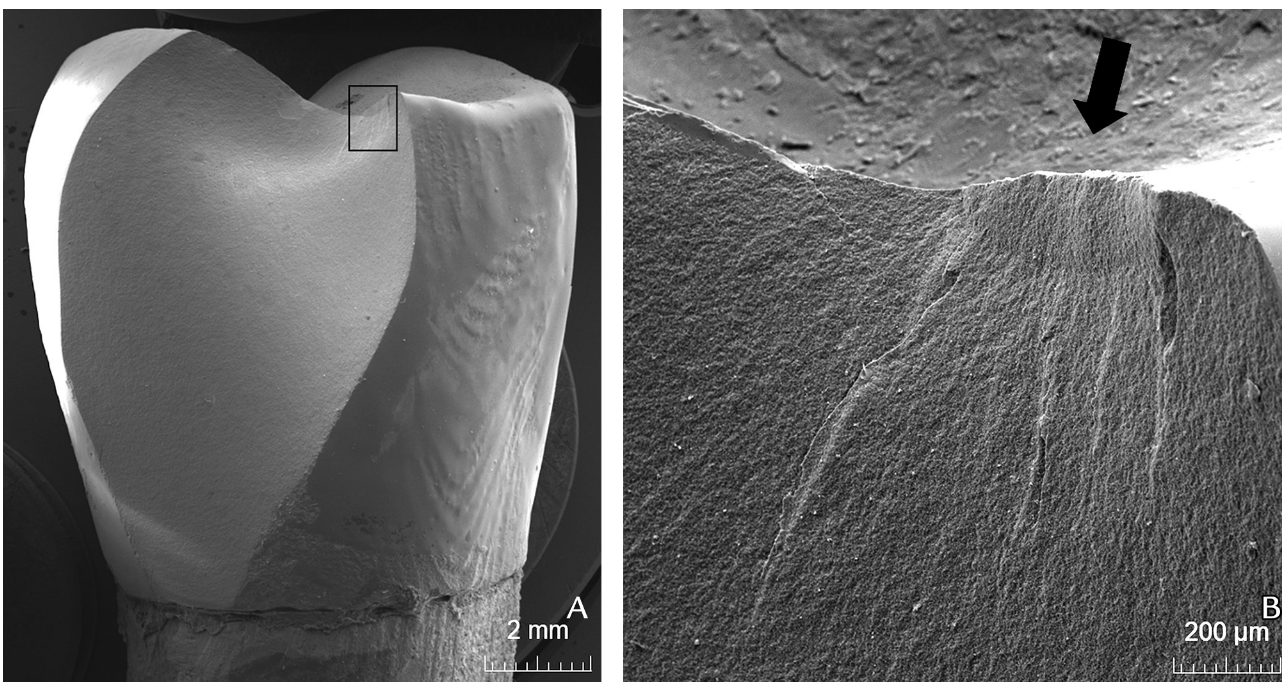

Figure 7. Representative scanning electron micrographs showing failure origin. A, Chipping failure with crack origin at occlusal surface (GA group, lifetime of 1×10^6 cycles). Original magnification ×50. B, Fracture origin indicated by *black arrow*. Original magnification ×400.

adjustment of lithium disilicate restorations,[21,23] removing the overglaze layer, and increasing the surface roughness.[21] Polishing the abraded ceramic surface with silicone finishers and polishing paste has the potential to reduce surface defects, resulting in a similar surface texture as with the overglaze protocol.[20-22] However, the lithium disilicate glass-ceramics have high crystalline content, elastic modulus, and hardness, which can reduce the effectiveness of the polishing treatment, leaving critical sharp defects at the restoration surface[23] that could explain the similar success rates between the GA and AP groups.

Transient and residual stresses are generated during the crystallization and glazing of glass-ceramics.[17,19] The presence of compressive stresses at the external surface of glass-ceramics after crystallization has been reported,[19] which could increase the fracture resistance of the restorations. Coating a glass-ceramic restoration with a low-fusion glass (overglaze) can reduce compressive stresses or even generate tensile stresses at the surface,[17] contributing to the propagation of subsurface and surface cracks[19] and decreasing the fatigue strength of the restoration.[17-19] The overglaze layer is predominantly a low-strength glass, which could have contributed to the higher nucleation and propagation of defects, resulting in a lower survival rate than for the polished restorations.[19,20]

The surface finishing resulted in different modes of failure, rejecting the third null hypothesis. Catastrophic failures initiating at the cementation surface, combined or not with surface cracks, were observed in the overglaze group and have been typically observed in the clinical situation.[7] Loading at the external surface leads to deflection of the restoration, resulting in high tensile stresses at the intaglio surface.[25] The overglaze layer can promote a homogeneous smoother external surface with a smaller population of sharp defects,[20,21] which can protect from cracking. This crack propagation resistance at the surface may have contributed to the observed catastrophic failures initiating at the interface.

For GA and AP restorations, cracks initiating at the external surface by abrasion and polishing can propagate at a higher speed than cracks initiating at the cementation surface,[2,3,13,37] resulting in a greater number of failures by cracking and chipping. These modes of failure initiated at the occlusal contact area (contact stresses) near the central groove, where the ceramic has a reduced thickness.[12,28,38] The crown geometry with different thicknesses in distinct regions, which is the typical clinical situation, may have contributed to the observed origin of failures and the mechanical performance of the restorations. In addition, axial loads applied to the occlusal functional slopes can result in cusp deflection in opposite directions, generating tensile stresses in the main groove area, which may have contributed to fractures initiating at that surface.[39]

Cyclic fatigue produces damage accumulation (subcritical crack growth) on lithium disilicate restorations,[11-14,24,32,35] with fractures occurring in the first cycles and at loads within the range of normal occlusal forces.[14,24,25,30,39] Ceramics are susceptible to a stress-corrosion process and to hydraulic pressure pumping during cyclic loading that accelerates the growth of cracks, reducing the time and load required for fractures.[11,14,25,32] Therefore, the wet environment, as for the oral condition, induces greater microstructural degradation of glass-ceramics.[24,32,35] Previous studies have reported that lithium disilicate restorations could survive shorter cycling times depending on the testing conditions.[8-10] They reported that the fatigue failure of the restorations was associated with cone cracks initiating at the occlusal surface similar to those found in the present study.[8,9]

The occlusal contact area between the restoration and the loading piston is reduced when using small-diameter pistons, resulting in a high contact pressure and tensile stresses of high magnitude at the surface.[17,29] Thus, the present study used anatomic pistons that fit the occlusal surface anatomy, with a 3-mm^2 contact area to simulate the occlusal wear facets. In this situation, the contact pressure was similar to that found in clinical service (38 N/mm^2).[29,33] The test protocol in the present study, which involved the fatigue testing of ceramic crowns adhesively cemented to a dentin analog preparation and loaded with an anatomic piston, was able to reproduce the modes of failure clinically observed within a normal occlusal load range.[9,30,36,37]

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The surface finish had no influence on the success rate of lithium disilicate crowns. However, considering the clinical implications of cracks (no need to replace the restoration), the polishing protocol had a positive impact on the survival of the restorations.
2. The mode of failure was associated with the surface finishing procedures: Overglazed crowns had a higher number of catastrophic failures; abrasion resulted in a greater frequency of chipping initiating at the external surface; and polishing was mostly associated with cracking (minor failures).

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Larissa Simião da Rocha: Conceptualization, Methodology, execution of the experimental protocols of the research. **Alvaro Della Bona:** Conceptualization, Methodology, interpretation of the SEM images and critically revising the manuscript. **Mauren Deprá Pretto:** Conceptualization, Methodology, execution of the experimental protocols of the research. **Pedro Henrique Corazza:** Conceptualization, Methodology, interpretation of the SEM images and critically revising the manuscript. **Marcia Borba:** Conceptualization, Methodology, data and failure analysis, Writing – original draft. **Paula Benetti:** Conceptualization, Methodology, data and failure analysis, Writing – original draft.

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