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Resin composite repair for implant-supported crowns

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Abstract: This study evaluated the reliability of implant-supported crowns repaired with resin composites. Fifty-four titanium abutments were divided in three groups (n = 18 each) to support resin nanoceramic molar crowns, as follows: (LU) (Lava Ultimate, 3M ESPE); LU repaired with either a direct or an indirect resin composite. Samples were subjected to mouth-motion accelerated-life testing in water (n = 18). Cumulative damage with a use stress of 300 N was used to plot Weibull curves for group comparison. Reliability was calculated for a mission of 100,000 cycles at 400 N load. Beta values were 0.83 for LU, 0.31 and 0.27 for LU repaired with Filtek and Ceramage, respectively. Weibull modulus for LU was 9.5 and η = 1047 N, m = 6.85, and η = 1002 N for LU repaired with Ceramage, and m = 4.65 and η = 766 N for LU repaired with Filtek ($p < 0.10$ between LU and LU repaired with Filtek). Reliability at 400 N was 100% for both LU and LU repaired with Ceramage which were significantly higher than LU Filtek repair (32%). LU restored crowns failed cohesively. Fractures were confined within the restored material, and detailed fractography is presented. The performance of resin nanoceramic material repaired with an indirect composite was maintained after accelerated-life testing compared to unrepaired controls. © 2016 Wiley Periodicals, Inc. J Biomed Mater Res Part B: Appl Biomater 00B: 000–000, 2016.

Key Words: dental implant, crown, repair, fatigue, fractography, resin composites

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INTRODUCTION

Since osseointegration of dental implants has been established as a predictable treatment modality,[1] there is increased demand for comprehensive understanding of the main complications eventually affecting prostheses success rates.[2,3] In a study comparing the clinical outcomes in older (before 2000) compared to more recent studies (after 2000), a call was made to clinicians and the scientific community to identify failures, complications and issues observed especially in implant prosthodontics. In general, whereas failure rates have decreased, substantial amount of time should still be expected by the patient for prostheses maintenance.[4] However, when considering the final prostheses material for implant-supported reconstructions, few studies have addressed the outcomes of all-ceramic materials, which are increasingly requested from both patients and dentists for improved esthetic results.[5]

Current use of all-ceramic alternatives for implant-supported crowns indicates a significant use of porcelain-fused to zirconia as a substitute for metal ceramics. Schwarz and colleagues have evaluated the survival rates for zirconia-based crowns for 2.1 years and have reported chipping frequency of 24.5% when compared to 9.5% for metal ceramics.[6] Improvements in the performance of this all-ceramic material were reported in another clinical study that found a chipping rate of 4% for porcelain-fused to zirconia and no failures for metal ceramics.[7] Apart from these studies comparing both materials, chipping rates for zirconia veneered reconstructions vary from 7.5% in 6 months[8] to 42.8% in 5 years.[9] Whereas results for tooth-supported reconstructions seem to be more encouraging, those for implant-supported crowns are still challenging and its use has been suggested, in an up to 9-year retrospective evaluation, as a risk factor for failure especially in the presence of an opposing ceramic reconstruction.[10]

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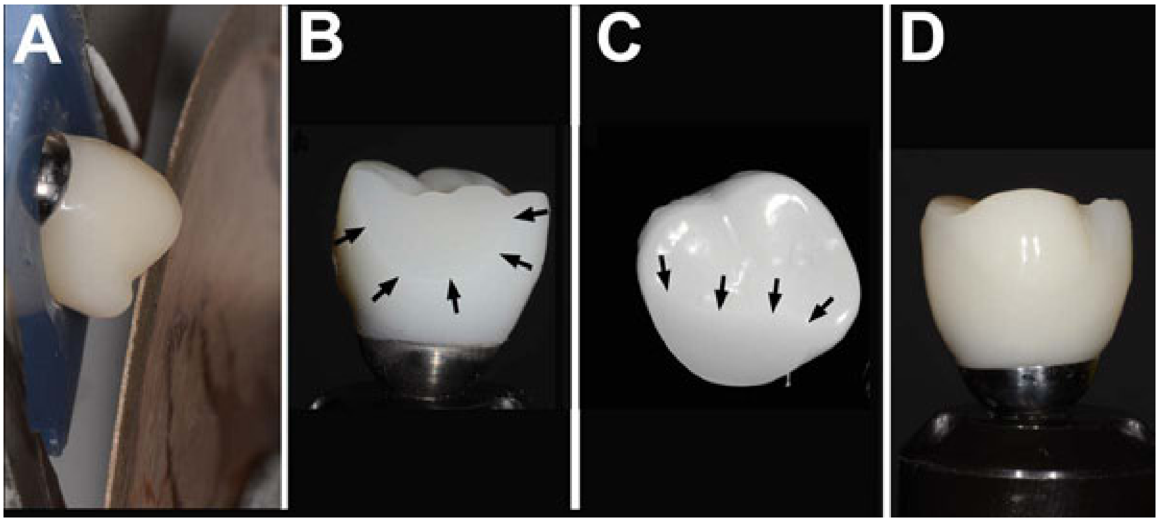

FIGURE 1. Standardization of removal of the mesio-lingual cusp of resin nanoceramic crowns. (A) A block was fabricated from custom tray material and fixed on a precision diamond saw machine to allow indexed and serial insertion and removal of the abutment and crown for cusp removal. (B and C) Respective lingual and occlusal views of the crown and the extension of cusp removal, and (D) the aspect of the crown after being restored with a resin composite.

While clinical trials reporting the successful use of zirconia-veneered implant-supported reconstructions, designed, and processed under specific handling conditions[11] are likely underway, the development of metal free alternatives such as resin-matrix ceramics has gained interest in implant prosthodontics.[12] This class of materials is characterized by the presence of polymeric matrices containing predominantly inorganic refractory compounds that may include glasses, ceramics, and glass ceramics.[13] These materials are claimed to have more resiliency compared to ceramics,[14,15] are easier to mill during computer assisted machining, more easily abraded for occlusal adjustments relative to ceramics, and have shown promising results in preclinical studies involving sliding fatigue testing when compared to metal ceramics for implant-supported crowns.[16–18]

On the other hand, after milling resin-matrix ceramic materials, the final esthetics may be limited considering that the blocks are usually monochromatic. Potential workarounds include staining, which is restricted to the outer layer, or milling an undersized prosthesis which is then hand-layered with resin composites of several shades and/or achromatic to achieve final anatomy and esthetics.[19] For the latter option, it is critical that the bonding between resin-matrix ceramics and the resin composite is strong enough to avoid interfacial failures.[20] It also is of utmost importance that such bond resists occlusal forces, especially when resin composites are used to repair these restorations. Repair is a commonly claimed advantage of resin-matrix ceramics, in general for their being exempted from the need of hydrofluoric acid etching, silane and bonding strategies required for glass-matrix ceramics or other more complex bonding steps involved in bonding to polycrystalline ceramics.

Bonding to resin-matrix-ceramic materials, such as resin nanoceramics, has been reported successful.[21] Considering the importance of bonding to resin nanoceramics for esthetic layering or repair, this study sought to evaluate the reliability and failure modes of implant-supported resin nanoceramic crowns repaired either with a direct or an indirect composite when subjected to mouth-motion accelerated-life testing in water. Our tested null hypothesis was that reliability was not significantly different between either indirect or direct composite repaired crowns when compared to non repaired intact crowns.

MATERIALS AND METHODS

Crown fabrication

Fifty-four Ti-6Al-4V abutments (Universal abutments, Bicon LLC, Boston, MA, USA) were selected for the study and divided in three groups ($n = 18$ each) to support resin nanoceramic maxillary first molar crowns (LU) (Lava Ultimate, 3M ESPE, St. Paul, MN). A waxed model maxillary first molar crown was replicated on a PlanScan-E4D Dentist CAD/CAM system (E4D Technologies, Richardson, TX, USA). Crowns were milled from Lava Ultimate blocks ($n = 54$, shade A3, 3M ESPE) in a PlanMill-E4D mill (E4D Technologies), polished with diamond paste and bristle brush, then buffed to a high gloss with a cotton buff. The bonding surface of each Lava Ultimate crown was sandblasted with a 240 mesh alumina (Ney-Brasive™ J.M. Ney Co., Bloomfield, CT, USA). Crowns were cleaned in an ultrasonic bath in ethanol, air dried, and their intaglio surface primed with RelyX Ceramic Primer (3M ESPE) applied with a microbrush, then dried with oil-free compressed air.

To standardize the removal of the mesio-lingual cusp for reliability evaluation of the repaired LU crowns, a block was created using a self-curing acrylic material (Fastray LC, Bosworth, IL, USA) to allow serial and indexed insertion and removal of crowns in a precision diamond saw machine (Isomet 2000, Buehler, Lake Bluff, IL, USA) [Figure 1(A–C)]. The size of cusp removal was intended to simulate the approximate fracture sizes initially observed for LU intact tested crowns and from previous fatigue testing of resin

TABLE I. Resin Composite Systems Used for Repair and Their Composition.

Material	Manufacturer	General Composition (as supplied by the manufacturer)
Ceramage	Shofu; Kyoto, Japan	Zirconium silicate featuring a progressively fine structural filling of more than 73% by weight of microfine ceramic particles in an organic polymer matrix
Filtek™ Supreme Ultra Universal Restorative	3M ESPE, MN, USA	Bis-GMA, UDMA, TEGDMA, and bis-EMA(6) resins. To moderate the shrinkage, PEGDMA has been substituted for a portion of the TEGDMA. The fillers are a combination of nonagglomerated/nonaggregated 20 nm silica filler, nonagglomerated/nonaggregated 4–11 nm zirconia filler, and aggregated zirconia/silica cluster filler (comprised of 20 nm silica and 4–11 nm zirconia particles)

composite crowns of the same anatomy and tested under identical step-stress accelerated-life testing profiles.[17,18]

To restore the crown anatomy, a silicone guide, made prior to cusp removal, was used to orient resin composite contouring. The created fracture sites were roughened by air abrasion (50 μm aluminum oxide), followed by cleaning in ultrasound with distilled water. A layer of adhesive (Adper™ Easy Bond, 3M ESPE, St. Paul, MN, USA) was applied to the roughened area and gently blown dry for 2–5 s to evaporate the ethanol solvent and light-cured for 10 s. Then, crowns had their mesio-lingual cusp repaired with either a direct (shade A1, Filtek™ Supreme Ultra Universal Restorative, 3M ESPE) or an indirect (shade A1, Ceramage, Shofu, Kyoto, Japan) resin composite (Table I). Finishing was accomplished with a series of polishing discs (Sof-Lex™, 3M ESPE), polishing with bristle brush and diamond paste and buffed to a high shine with a small muslin rag wheel [Figure 1(D)].

A crown/implant positioning apparatus was fabricated to allow repeated pouring of the self-curing acrylic resin (Orthodontic resin, Dentsply Caulk, Milford, DE, USA) and standardized embedding of samples to be fixed on the testing machine. PVC tubing and a silicone matrix with the cemented crown embedded and the abutment connected to the implants (3 mm well, 8 mm height, Bicon, Boston, MA, USA, $n = 18$ each group) were used. The sectioned PVC tube was positioned over the silicone key containing the implant/abutment/crown assembly in the center. Then, self-curing acrylic resin was poured with the implant/abutment interface remaining 1 mm below the potting surface.

Mouth-motion step-stress accelerated-life testing (SSALT) and reliability analysis

Three extra crowns from the Lava Ultimate group were subjected to single load to fracture (SLF) testing with a spherical indenter (6 mm diameter, D-2 Steel) positioned at the mesio-lingual cusp at a crosshead speed of 1 mm/min (Model 800R, Test Resources, Inc., Shakopee, MN, USA).[18] Failure was defined as veneer material fracture. The mean load to failure values were used to determine step-stress profiles for accelerated-life fatigue testing, undertaken in the remaining samples ($n = 18$, each group) for probability of survival calculation.

Mouth-motion step-stress accelerated-life testing was performed in an axial direction at constant frequency of 2 Hz with the spherical indenter positioned at the same cusp incline as done for the SLF test, which allowed for sliding of the indenter (0.3–0.5 mm). Crowns were submerged in water at room temperature throughout mechanical testing. Although details of the SSALT method used in this study has been reported elsewhere,[22–26] in brief, three profiles are designed as mild, moderate, and aggressive, with the number of specimens assigned to each group being distributed in the ratios of 3:2:1, respectively (i.e., $n = 9$ in the mild, $n = 6$ in the moderate, and $n = 3$ in the aggressive load profile). These profiles are named based on the step-wise load increase that the specimen will be fatigued throughout the cycles until a certain level of load, meaning that specimens assigned to a mild profile will be cycled longer to reach the same load level of a specimen assigned to the aggressive profile. Fatigue loads throughout SSALT ranged from 200 N up to a maximum of 1200 N with a steady increase in load as a function of elapsed cycles. Samples that survived the maximum fatigue load (no fracture) were deemed suspended and accounted for in reliability calculations.

Based upon the step-stress distribution of the failures, a cumulative damage model Weibull distribution was used with a use stress of 300 N (90% two-sided confidence intervals) to plot Weibull curves for group comparison (Reliasoft Synthesis 9, Alta, Tucson, AZ, USA). Reliability (the probability of an item functioning for a given amount of time without failure) was then calculated for completion of a mission of 100,000 cycles at 400 N load for group comparison. If the Weibull use level probability calculated Beta were <1 for any group (which indicates that failure rates over time decrease), then a Probability Weibull Contour plot (Weibull modulus vs. characteristic strength) was calculated (Synthesis Weibull ++9, Reliasoft, Tucson, AZ, USA) using final load magnitude to failure of all groups. The Weibull modulus (m) and characteristic strength Eta (η) (63.2% of the specimens would fail up to the calculated "η") were identified for examining differences between groups.

Failed samples were first inspected in polarized light stereomicroscope (MZ-APO, Carl Zeiss Micro Imaging, Thornwood, NY, USA) and then at a scanning electron microscope (SEM) (Model 3500S, Hitachi Ltd., Osaka, Japan)

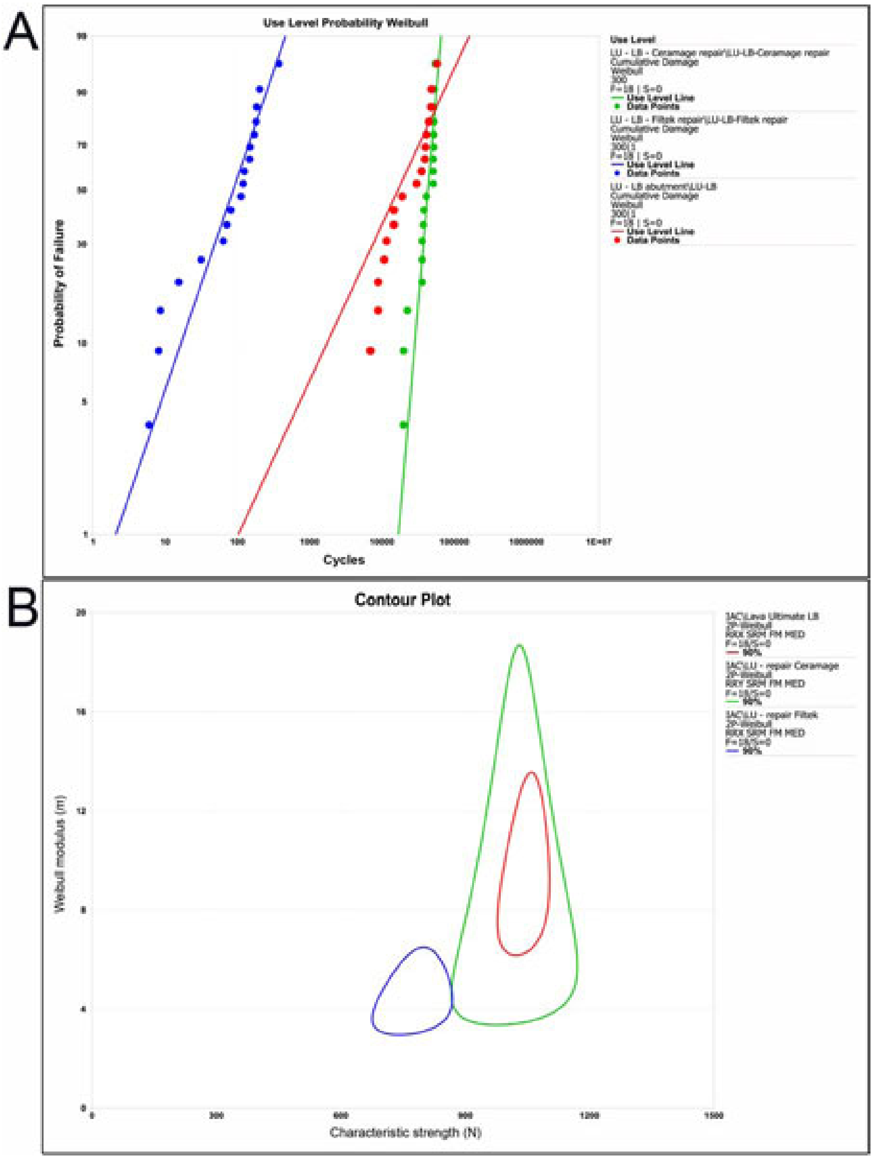

FIGURE 2. (A) Use level probability Weibull plot for use stress of 300 N showing the probability of failure as a function of cycles for all groups. (B) Contour plot for the relationship between shape parameters (m) and characteristic strength (η) depicts an overlap between the contours of resin nanoceramic and crowns repaired with Ceramage, indicating that they are not statistically different. There is also an overlap between the latter and crowns repaired with Filtek, whereas a significant difference in characteristic strength is only observed between resin nanoceramic and Filtek repair (nonoverlap between contours).

for fractographic analysis. Criteria used for failure were cohesive fracture within the restored resin composite (chipping), fracture involving the bonded interface between composites, delamination (abutment exposure), crown debonding from abutment, and abutment fracture.

RESULTS

SLF mean values were 1718 N (±132) for Lava Ultimate crowns. Use level probability Weibull calculation (probability of failure vs. cycles) with use stress of 300 N and 90% two-sided confidence intervals showed a Beta (β) of 0.83 for Lava Ultimate, 0.31 for LU repaired with Filtek, and 0.27 for LU repaired with Ceramage [Figure 2(A)]. These β values indicate that fatigue did not accelerate the failure of any crown's group, whereas load alone dictated the failure. There were no suspensions as all crowns failed during sliding fatigue.

Since the Weibull use level probability calculated Beta was <1 for all groups, a Probability Weibull Contour plot (Weibull modulus vs. Characteristic Strength) was calculated using final fatigue load to failure or survival of all groups. The Weibull modulus (90% two-sided confidence intervals) was calculated using the Fisher Matrix method. All possible combinations between Weibull modulus (m) and characteristic strength Eta (η) (63.2% of the specimens would fail up to the calculated "η") were statistically determined within 90% confidence intervals for examining potential differences

TABLE II. The Reliability Values Were Not Significantly Different Between Lava Ultimate and LU Ceramage Repaired Crowns, and Both Were Significantly Higher Compared to LU Filtek Repair (Nonoverlap Between Upper and Lower Bounds, $p < 0.1$)

	Lava Ultimate	LU Filtek repair	LU Ceramage repair
Upper bound	100	53	100
Reliability (%) 100,000 cycles @ 400 N	**100**[a]	**32**[b]	**100**[a]
Lower bound	98	13	89

Same superscript letters indicate statistical homogeneous groups.

between groups [Figure 2(B)]. Characteristic strength values were not different between Lava Ultimate ($\eta = 1047$ N) and Lava Ultimate repaired with Ceramage ($\eta = 1002$ N), and also not different between the latter and Lava Ultimate repaired with Filtek ($\eta = 766$ N) as noticed by the existing contour overlap between groups, meaning that samples are considered to be from the same population[27] [Figure 2(B)]. To further confirm the difference between LU repaired groups (given that contours overlap was visually uncertain between these groups), plot critical level was used to calculate and display the minimum confidence level at which the two plots intersect. The calculated minimum confidence level was 89.49% (90% confidence bounds used), defining the overlap and thus resin nanoceramic repaired groups were not significantly different for load at failure during fatigue (for any confidence level above the critical level, the contour plots overlap, meaning the absence of a statistical difference between the data sets). The higher Weibull modulus for LU ($m = 9.5$) compared to LU repaired with Ceramage ($m = 6.85$), and LU repaired with Filtek ($m = 4.65$) suggests that flaws were more uniformly distributed in the unrepaired LU crowns, resulting in failures occurring in a more anticipated load range compared to the other groups [Figure 2(B)].

Reliability for completion of a mission of 100,000 cycles at 400 N (Table II) showed no differences in reliability between Lava Ultimate and LU Ceramage repaired crowns. Both groups presented higher reliability compared to crowns in the LU Filtek repair. Reliability values, presented as percentage, indicated that for a mission of 100,000 cycles, cumulative damage from loads reaching 400 N would lead to survival of 100% of Lava Ultimate and LU Ceramage repaired crowns, compared to 32% of LU Filtek repaired crowns.

Fractographic analysis

Resin nanoceramic crowns presented cohesive fractures that allowed characterization under the SEM and the depiction of arrest lines and hackles indicating the direction of crack propagation (Figure 3). Lava Ultimate restored crowns from both groups presented failures chiefly restricted to the restored composite (Figures 4 and 5), rarely involving the bonded interface or the underlying resin nanoceramic crown. Fracture origin was located on the occlusal contact sliding surface with crack front propagating toward the margins of the fractured surface.

DISCUSSION

Maintenance feasibility in veneered implant-supported prostheses is considered important given expected complication rates.[28–30] While the literature lacks consensus regarding the criteria and terminology of fracture severity and subsequent treatment approaches, clinicians are eventually faced with the decision of repolishing, repair, or change the prostheses.[31] Because any such approaches result in additional chair time and cost, the reliability of such procedures should be characterized. Our fatigue testing showed that the probability of survival of resin nanoceramic implant-supported crowns repaired with Ceramage was not significantly different from non repaired intact crowns. Conversely, repair with the direct composite Filtek led to a significant decrease in probability of survival. However, although the same trend in differences between groups for fatigue load

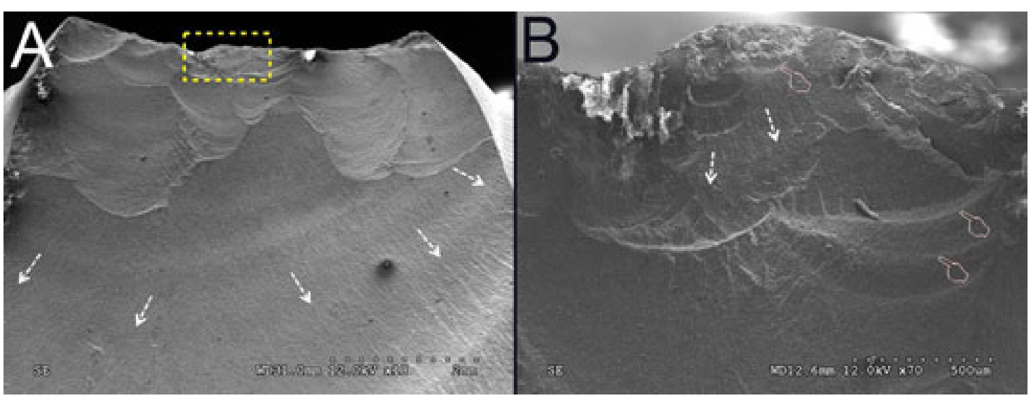

FIGURE 3. SEM micrographs of a resin nanoceramic crown failed at 1200 N in the mild profile. Crowns failing at higher loads presented larger fractures, as shown in a lingual view (A) where it depicts the occlusal indentation area (dotted square) and crack propagation from there toward the margins of the fractured surface confirmed by the presence of hackles (dotted arrows). (B) Magnification of the dotted square shown in (A) shows the indentation area, the resulting surface damage, and several arrest lines (pointers) confirming fracture origin and the direction of crack propagation toward the margins.

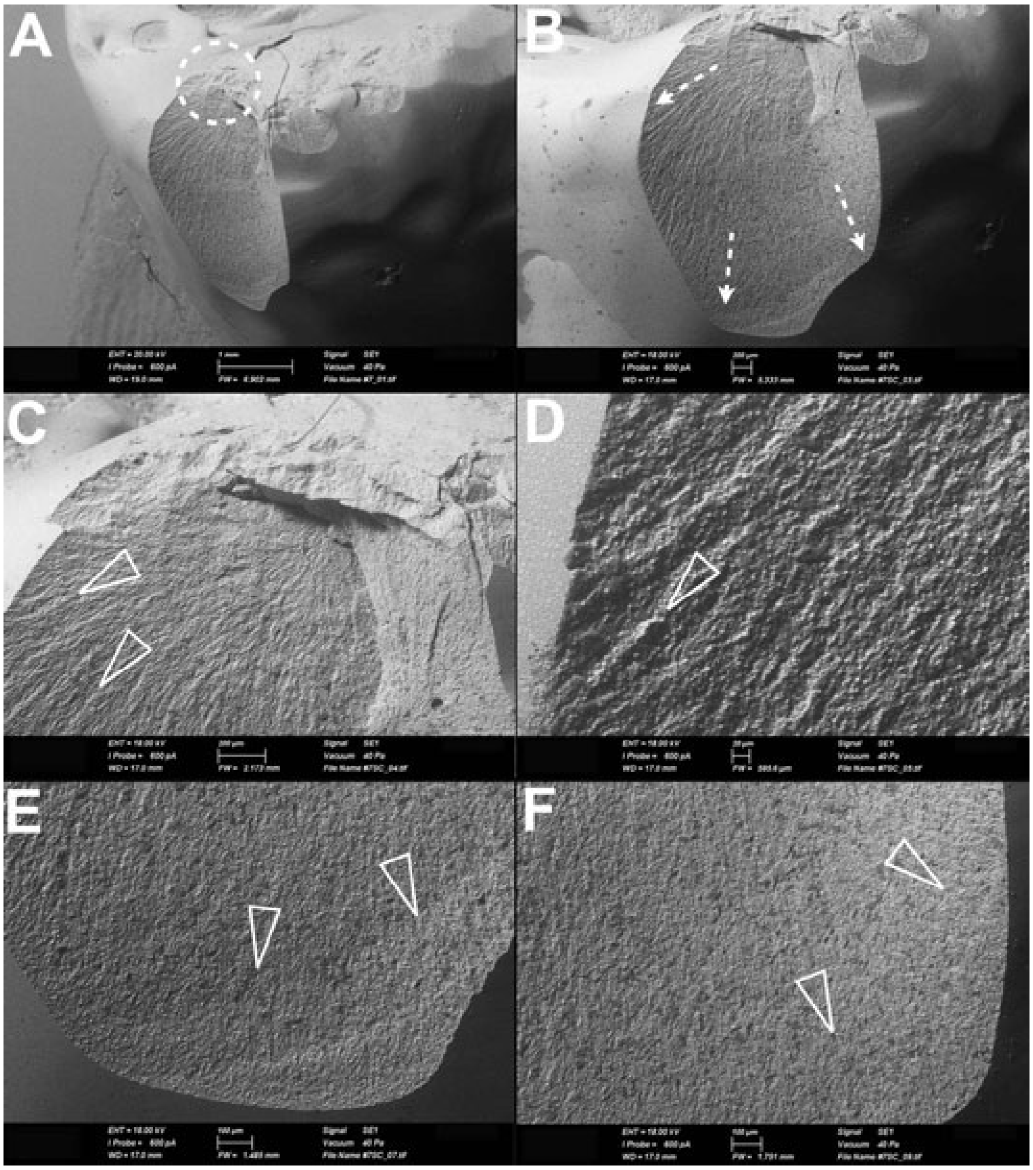

FIGURE 4. Representative SEM micrographs showing the failure mode of a resin nanoceramic crown repaired with Ceramage. (A) Occlusal view of the fracture and of the indentation contact (dotted circle). Note that fracture extension is limited to the repaired composite. (B) Lingual overview of fracture showing the direction of crack propagation (dotted arrows) depicted by its several hackles. (C–F) Counter-clockwise magnifications of the dotted arrows shown in (B) which confirm the presence of hackles (arrowhead) and crack propagation from the occlusal indentation surface toward the fractured margins.

values at failure were observed in the contour plot, the characteristic strength was high for all groups if the average range of functional loads at the molar region (700 N) is considered.[32,33]

In spite of the fact that Weibull modulus, which measures the variability of the results, was not statistically different between resin nanoceramic and repaired Ceramage crowns, its higher value for the former was expected given that it is likely the result of inherent flaws created during hand-layering with Ceramage, whereas it is minimized when a block is milled out of a densely packed material.[34,35] When an indirect resin composite, such as the one used in the present study, is directly layered onto an abutment (e.g., as an IAC®) voids are also introduced during layering, which may, in combination with microstructure, composition, and other factors, decrease its probability of survival when compared to the same crown material fabricated through CAD/CAM.[36] This assumption warrants further investigation through advanced imaging and quantification.

The resin nanoceramic block is comprised by nanomer and nanocluster fillers (silica nanomers of 20 nm diameter and zirconia nanomers of 4– 11 nm diameter) with a total nanoceramic material content by weight of approximately 80%. The engineered nanoparticles are treated with a silane-coupling agent using a proprietary method. This functionalized silane bonds chemically to the nanoceramic surface as well as to the resin matrix.[13] Bonding to this material to repair a missing cusp, as simulated herein,

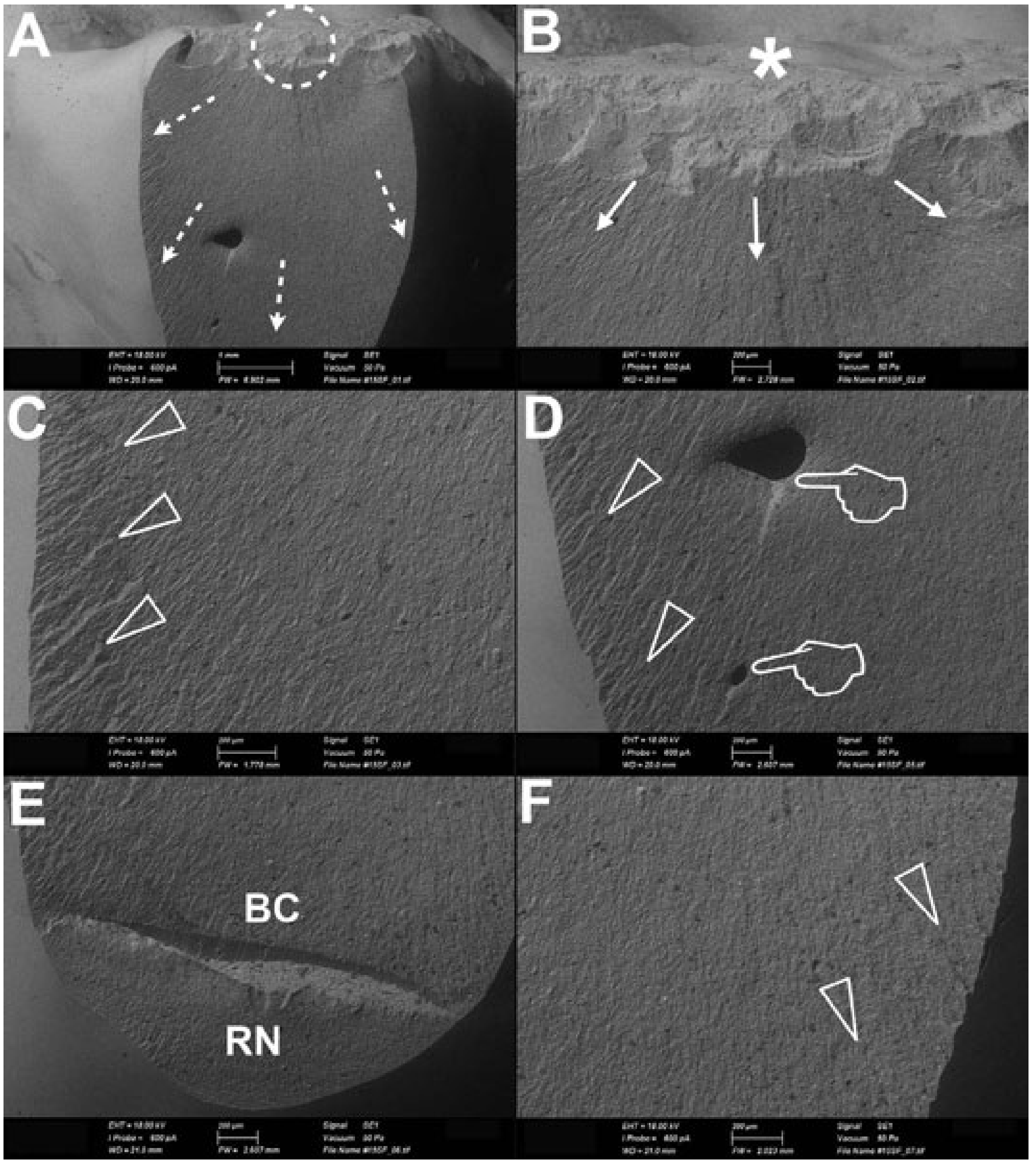

FIGURE 5. Representative SEM micrographs of the failure mode of a resin nanoceramic crown repaired with Filtek. (A) Lingual view shows the fracture extension and the direction of crack propagation from the occlusal (dotted circle) toward the margins of the crown (dotted arrows). (B) Magnified view of the dotted circle shows the surface damage caused by the indenter and the presence of arrest lines with their concave portions pointing toward the origin (occlusal surface) and its propagation toward the margins of the crowns (arrows). (C–F) Counter-clockwise magnifications of the dotted arrows shown in (A). In C, D, and F several hackles (arrow heads) confirm the direction of crack propagation toward the margins of the fractured surface. Wake hackles (pointers), which are hackles extending from a singularity at the crack front in the direction of crackling, were observed in (D). Such porosities were likely introduced during composite hand-layering. Whereas most failures were confined to the bonded composite (BC), (E) An instance where the crack went through the interface leading to a continued fractured in the resin nanoceramic (RN) material as well.

involved further increase in surface texture, which can be accomplished with burs or by sandblasting, followed by the use of conventional adhesive systems. Since failures did not involve the bonded interface of composite resins, reliability values likely resulted from differences in mechanical properties between the used direct compared to the indirect material.

Bonding to glass-matrix ceramics involves acid-etching with a highly corrosive and toxic hydrofluoric acid, followed by silanization and bonding procedures that will allow the insertion of a resin composite with different mechanical and optical properties.[12] In porcelain-fused to zirconia reconstructions, should chipping expose the coping, an additional challenge in repair is faced as bonding to polycrystalline ceramics and the surrounding glass-based porcelain becomes more complex.[37] In contrast, repair of resin-matrix ceramics involves either sandblasting, as performed in this study, or bur roughening followed by adhesive treatment and placement of a composite with similar mechanical and optical properties.[12]

Fractures in resin nanoceramic crowns were cohesive and never exposed the supporting abutment. Considering that all prostheses were directly cemented onto the abutments as Integrated Abutment Crowns (no framework), the failure mechanisms suggests that recommendations traditionally made for porcelain veneered reconstructions, regarding the need of a substructure designed to provide porcelain even thickness,[35,38,39] should be revisited for resin-matrix ceramics. As shown in this study and previously,[36] no substructure supporting the final crown was present, resulting in substantial amounts of "unsupported" material. Still, the required amount of support, if any, is yet to be determined for this class of material.

Finally, our choice of purely tapered interference fit implant-abutment connection design that exempts an abutment screw was aimed at avoiding abutment screw fractures or even abutment fractures shown to occur at lower load levels than those required for materials failure evaluated herein.[40–44] This means that based on previous testing conducted under the same methodology, resin nanoceramic crowns would likely survive fatigue if tested on abutment screwed implant systems given that their components (screw, abutment screws) would fail before fracture of the crown material.[40,43–48] Since the abutment used in this study is monolithic Ti-6Al-4V (no abutment screw access) stabilized by pure interference fit mechanics,[49,50] testing could focus on the failure and probability of survival calculation of the materials *per se*, as initially aimed for. In addition, due to the retrievability easiness of the prosthesis/abutment assembly, a feature of this type of connection, composites can be placed by either a direct chairside or an indirect laboratory repair procedure.

The postulated null hypothesis that reliability was not significantly different between a direct or an indirect composite compared to the intact resin nanoceramic material was partially rejected. Reliability was not significantly different between intact resin nanoceramic crowns and those repaired with an indirect composite, but both were higher compared to crowns repaired with a direct composite.

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