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Abutment Design for Implant-Supported Indirect Composite Molar Crowns: Reliability and Fractography

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Keywords
Indirect composites; fatigue; reliability; fractography; Weibull; crowns; implants.

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This study was supported by FAPESP grant # 2010/06152–9, Brazil.

Accepted January 24, 2012

doi: 10.1111/j.1532-849X.2012.00872.x

Abstract

Purpose: To investigate the reliability of titanium abutments veneered with indirect composites for implant-supported crowns and the possibility to trace back the fracture origin by qualitative fractographic analysis.
Materials and Methods: Large base (LB) (6.4-mm diameter base, with a 4-mm high cone in the center for composite retention), small base (SB-4) (5.2-mm base, 4-mm high cone), and small base with cone shortened to 2 mm (SB-2) Ti abutments were used. Each abutment received incremental layers of indirect resin composite until completing the anatomy of a maxillary molar crown. Step-stress accelerated-life fatigue testing ($n = 18$ each) was performed in water. Weibull curves with use stress of 200 N for 50,000 and 100,000 cycles were calculated. Probability Weibull plots examined the differences between groups. Specimens were inspected in light-polarized and scanning electron microscopes for fractographic analysis.
Results: Use level probability Weibull plots showed Beta values of 0.27 for LB, 0.32 for SB-4, and 0.26 for SB-2, indicating that failures were not influenced by fatigue and damage accumulation. The data replotted as Weibull distribution showed no significant difference in the characteristic strengths between LB (794 N) and SB-4 abutments (836 N), which were both significantly higher than SB-2 (601 N). Failure mode was cohesive within the composite for all groups. Fractographic markings showed that failures initiated at the indentation area and propagated toward the margins of cohesively failed composite.
Conclusions: Reliability was not influenced by abutment design. Qualitative fractographic analysis of the failed indirect composite was feasible.

Following the definition of osseointegration,[1] an abundant literature database on the survival of a variety of implant systems has been created and to date, a predictable outcome can be expected for implant fixtures.[2] The consistent reports of success rates often exceeding 90% over 10 years have made implant dentistry a highly predictable treatment.[3-5] However, it has been noted that considerably less efforts have been devoted to characterizing the survival and failure modes of the different types of implant-supported restorations.[6] This is particularly surprising considering that complications are usually more frequent for implant-supported prostheses than conventional tooth-supported prostheses.[7]

The most common technical complication for a tooth-supported restoration is loss of retention, whereas for an implant-supported restoration it is fracture of the veneering material, be it ceramic or composite,[7] which may require repair or replacement of the restoration. Several engineering parameters have been emphasized for the design of long-term clinical performance of crown systems, such as the role of material properties, prosthesis design, fabrication operations, and others.[8] In addition, observations of patient- and implant-specific predictors of failure of implant-supported metal ceramic crowns and fixed dental prostheses (FDPs) have identified that porcelain fractures seem to occur at higher rates when opposing another metal ceramic implant-supported restoration, or in the presence of bruxism, or in the absence of a stabilization appliance.[9]

The search for more esthetic alternatives to metal ceramics has brought all-ceramic restorations to the implant restorative field. Interestingly, only the survival rates of tooth-supported densely sintered alumina and reinforced glass-ceramic crowns are comparable to those of metal-ceramics.[10] However, in an implant-supported scenario, metal ceramic crowns present, in general, higher survival rates in the posterior area than all-ceramic crowns do.[11] When all-ceramic materials of high fracture toughness, such as zirconium oxide, were used, the chipping within the porcelain veneer frequently observed in tooth-supported FDPs[12,13] persisted in implant-supported reconstructions with failure rates up to 53% in 2 years.[14,15]

As an alternative, the concept of using indirect composites directly applied onto titanium abutments as a bulk restorative material, known as the integrated abutment crown (IAC™) has been described.[16] The procedure involves chemomechanical bonding of an indirect composite, which is incrementally packed to the Ti abutment and light-cured until completion of the desired anatomy. The crown and abutment are one cementless and screwless unit, where the tapered (3°) interference fit abutment connects to the implant well.[16,17] Recent load-to-failure testing of molar crowns made from three indirect composites used for IACs™ has shown failures occurring at loads higher than those observed in normal occlusal function and not significantly different from metal ceramic crowns tested as controls and known as a gold standard.[18] A potential advantage in the use of composite for implant-supported restorations is that should proximal contacts be improved or the restoration's anatomy require slight alterations to favor esthetics, the adding of composite can be accomplished intraorally, in contrast to a porcelain-veneered restoration that would demand additional work by the technician and another visit by the patient.

The abutments used for IACs™ may have different configurations of base width and cone height. The cone, located in the center of the abutment, is meant to provide mechanical retention to the composite. Should there be any occlusal clearance constraints, it may be necessary to shorten the post to accommodate the resin. Similarly, reduced proximal width may limit the placement of an abutment with a larger base. Since the mechanical implications of altering abutment support scenarios such as reducing abutment cone height and base width in the reliability and failure modes of IACs™ are unknown, this study sought to test the following null hypotheses: (1) step-stress R-ratio fatigue is not a factor accelerating the failure of IACs™ with different experimental abutment configurations and (2) determination of fracture origin and crack front propagation is not possible in the tested indirect composite by means of qualitative fractographic analysis.

Materials and methods

Crown fabrication

A total of 63 experimental titanium alloy (Ti-6Al-4V) locking taper abutments (Bicon LLC, Boston, MA) with three configurations (n = 21 each) were used. The abutments presented either of the following dimensions: large base abutments (LB) (6.4-mm diameter base, with a 4-mm height and 2-mm diameter cone in the center for indirect composite retention); small base (SB-4) (5.2-mm base, 4-mm height, and 2-mm diameter cone); or small base (SB-2) with the center cone shortened to a 2-mm height (Fig 1).

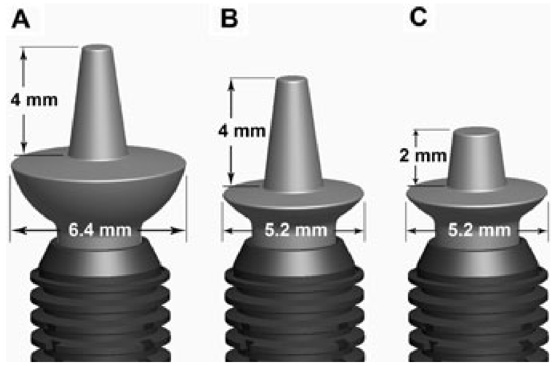

Figure 1 Abutment configurations tested: (A) LB, (B) SB-4, and (C) SB-2.

For crown fabrication in the dental laboratory, the cone and base of all abutments were grit-blasted prior to the application of the indirect composite material. To avoid roughness inclusions on the taper interference fit connection area, the stem of each abutment was protected with wax during sandblasting (50 μm aluminum oxide particles, 0.55 MPa at 1 cm distance). The abutments were cleaned in an ultrasound ethyl alcohol bath for 12 minutes and dried in wet/oil-free air. A layer of metal primer (M.L. Primer, Shofu, Kyoto, Japan) was applied and left undisturbed for 45 seconds. Incremental layers of the indirect composite material (Ceramage, Shofu) were veneered according to the manufacturer's instructions. The material composition, as supplied by the manufacturer, describes a composite containing zirconium silicate featuring a progressively fine structural filling of more than 73% by weight of microfine ceramic particles in an organic polymer matrix. According to the manufacturer's information, Ceramage's flexural strength is 146 MPa, its modulus of elasticity is 10.7 GPa, and its Vickers hardness is 726 MPa.

A silicon impression of a waxed maxillary first molar crown's desired anatomy was used to guide incremental resin build-up and standardize the crown's final contour. A preopaque layer followed by a dentin resin (shade A3) was applied and light-cured (DiamondLite Fotokur F/X laboratory halogen light booth, DRM, Branford, CT, at 500 mW/cm^2) for 3 minutes. Incremental layers of body resin (shade A3) were applied, followed by incisal resin, each light-cured for 5 minutes. A final curing cycle was performed after complete resin build-up. Finishing and polishing steps included the use of carbide burs in a slow-speed handpiece, followed by silicon brushes, rubber tips, and polishing paste (CompoShine, Shofu) applied with a muslin buff. The specimens were allowed to age in water for 7 days at room temperature prior to testing. One additional crown of each group was fabricated and embedded in epoxy resin (Epofix Resin, Struers, Ballerup, Denmark) and polished in a mesial to distal orientation (SiC papers #600, #1200, #2000, and #4000) to verify composite thickness and support provided by the different abutment configurations (Fig 2).

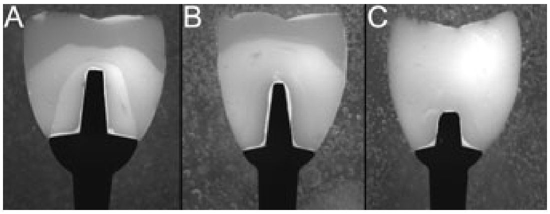

Figure 2 Sectioned crowns of the: (A) LB, (B) SB-4, and (C) SB-2 groups.

Mechanical testing

The fabrication of a standardized positioning apparatus for the testing machine was accomplished using PVC tubing and a silicone matrix with the final IAC™ embedded (occlusal surface down) and its abutment connected to the implant analogue well (3-mm well, 8-mm height, Bicon) exposed to orient its axial position. The tubing was sectioned and positioned over the silicone key containing the implant analogue/abutment assembly in the center. Then, self-curing acrylic resin (Orthodontic resin, Dentsply Caulk, Milford, DE) was poured, leaving 1 mm of the implant abutment replicas' finishing line exposed above the potting surface.

Twenty-one crowns of each abutment configuration were fabricated. Three crowns were subjected to a single axial load-to-fracture test with a flat indenter positioned at the mesiolingual centric holding cusp at a 1 mm/min cross-head speed (Model 800R, Test Resources, Inc., Shakopee, MN).[19] Failure was defined as composite chip or bulk fracture, and it was monitored in the load/displacement curves. Load versus displacement curves were recorded for each specimen, so the mean load to failure for each material could be used in determining step-stress profiles for reliability testing. Fatigue testing was undertaken in the remaining specimens (n = 18/group) at step-stress levels for timely fracture and reliability calculation.

Fatigue was performed in an axial direction at constant frequency (f = 2 Hz) with the flat indenter positioned at the same cusp location as done for the single load to fracture test. Step-stress load profiles started at a load of approximately 20% of the mean load-to-failure values. Details of the fatigue method used in this study are found elsewhere.[20–24] In essence, 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 stepwise 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 (Fig 3). Step-stress fatigue testing was performed in R-ratio fatigue mode with an oscillating load between the maximum load within the step cycle and a minimum load above 0 and below 10 N. In this method, the indenter does not leave the specimen surface. Crowns were submerged in water during loading at room temperature.

Reliability and fractographic analysis

Based upon the step-stress distribution of the failures, use level probability Weibull curves (probability of failure vs. cycles) with a 200 N use stress and 90% two-sided confidence intervals were calculated and plotted (Alta Pro 7, ReliaSoft, Tucson, AZ) using a power law relationship for damage accumulation. Reliability (the probability of an item functioning for a given amount of time without failure) for completion of a mission of 50,000 and 100,000 cycles at 200 N (90% two-sided confidence interval) was calculated from the Weibull curves for group comparisons. If the Weibull use level probability calculated Beta was <1 for any group, then a Probability Weibull Contour plot (Weibull modulus vs. Eta) was calculated using final load magnitude to failure or survival of all groups. The Weibull modulus (90% two-sided confidence intervals) was calculated (Weibull 7++, Reliasoft, Tucson, AZ) using the Fisher Matrix method. Weibull modulus (*m*) and characteristic strength

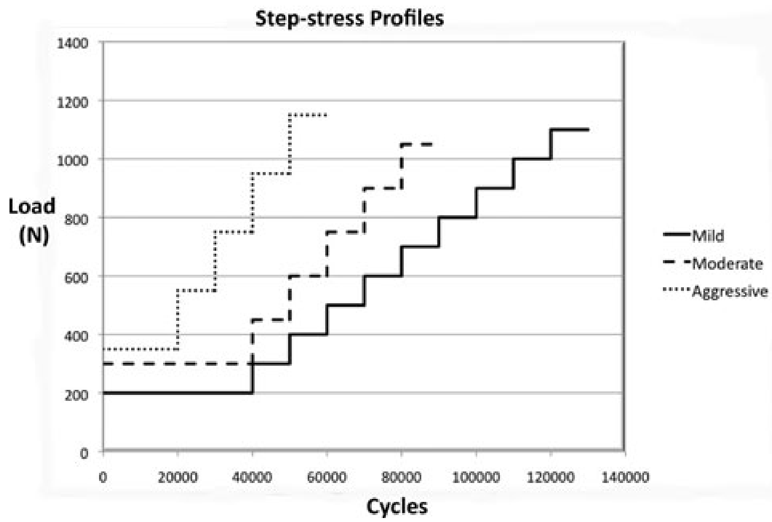

Figure 3 Mild, moderate, and aggressive profiles used for accelerated fatigue testing of the different abutment designs.

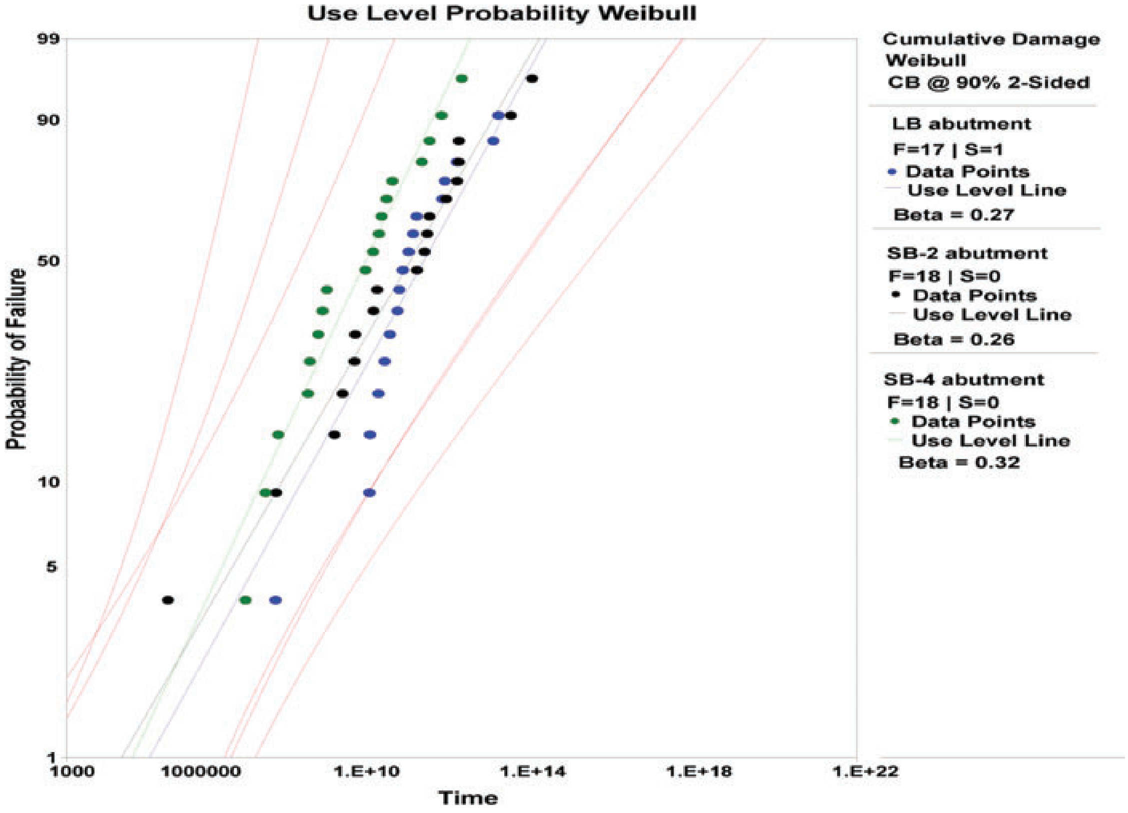

Figure 4 Probability of failure versus cycles plot (90% two-sided confidence bounds) at a 200 N use stress for LB, SB-4, and SB-2 groups.

Eta (η) (63.2% of the specimens would fail up to the calculated "η") were identified for examining differences between groups.

Failed specimens were first inspected in a polarized light stereomicroscope (MZ-APO, Carl Zeiss Micro Imaging, Thornwood, NY) and subsequently gold sputtered (Emitech K650, Emitech Products Inc., Houston, TX) for fractographic analysis using a scanning electron microscope (SEM) (Model 3500S, Hitachi Ltd., Osaka, Japan). Criteria used for failure were delamination (abutment exposure), cohesive fracture

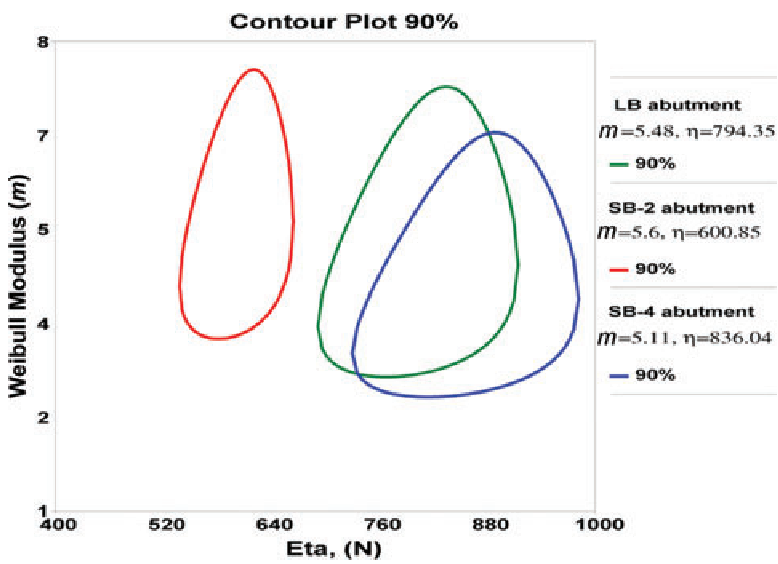

Figure 5 Probability Weibull contour plot (Weibull modulus vs. Eta) for the different abutment configurations. Note that the significantly lower characteristic strength (Eta) observed for SB-2 (600.85 N) when compared to LB (794.35 N) and SB-4 (836.04 N) is graphically seen as the nonoverlap between groups.

Table 1 Reliability for completion of 50,000 cycles at 200 N and 100,000 cycles at the same load level

50,000 cycles at 200 N			
Output	LB	SB-4	SB-2
Upper limit	0.9984	0.9979	0.9973
Reliability	0.9917	0.989	0.9874
Lower limit	0.9575	0.9434	0.9414
100,000 cycles at 200 N			
Output	LB	SB-4	SB-2
Upper limit	0.998	0.9974	0.9967
Reliability	0.9899	0.9863	0.9848
Lower limit	0.9496	0.9299	0.9323

No statistical differences between groups for either simulations, as observed by the overlap between upper and lower limits ($p > 0.10$).

within the composite (chipping), crown debond from abutment, or abutment fracture.

Results

Mechanical testing

The mean values observed in the single load to fracture tests were 1126 ± 259 N for LB, 1079 ± 280 N for SB-4, and 1018 ± 243 N for SB-2. The use level probability Weibull plots at use stress of 200 N (90% two-sided confidence intervals) showed an overlap of the confidence intervals between groups (Fig 4), indicating no statistical difference ($p > 0.10$). The β values were 0.27 for the LB abutments, 0.32 for SB-4, and 0.26 for SB-2, as shown in the plot, indicating that fatigue was not an acceleration factor, while strength was the main element dictating the failure. Note that this β describes failure rate changes over time and does not correlate to Weibull modulus, where higher m values indicate that the material is consistent and flaws are distributed uniformly throughout the material.

The data replotted according to the fatigue load at failure using a probability Weibull distribution showed a Weibull modulus of $m = 5.48$ for LB, $m = 5.11$ for SB-4, and $m = 5.6$ for SB-2. The characteristic strength (η, which indicates the load at which 63.2% of the specimens of each group would fail) was significantly higher ($p < 0.10$) for LB and SB-4 ($\eta = 794.35$ N and $\eta = 836.04$ N, respectively) than for SB-2 ($\eta = 600.85$ N). An instructive way to graphically present this data is by using a Weibull parameter contour plot, which shows statistical differences based upon non overlap of the confidence bounds (Fig 5).

The calculated reliability (two-sided 90% confidence intervals) for the different abutment configurations is listed in Table 1. Reliability for completion of 50,000 cycles at 200 N showed percentage values indicating cumulative damages from loads reaching 200 N would lead to crown survival in 99% of the LB abutments, 98% of SB-4, and 98% of SB-2. The overlap between the upper and lower limits indicates no statistical difference. No significant change in reliability was observed for completion of 100,000 cycles at the same load level between groups.

Fractographic analysis

Failures were cohesive within the indirect composite for all groups and involved the fatigued cusp with no extension to proximal areas (Fig 6). The presence of hackles and wake hackles on the fractured surface indicated that the crack originated at the indentation area and propagated toward the margins of the fractured surface. In general, failures occurring at lower load levels (approximately 500 N) were more limited in size (Figs 7A and B), cohesive within the composite, and started at the indentation area as well. Four specimens in group SB-4, failing at a 1000 N load, presented ductile fracture of the cone base. The micrographs (Figs 7C and D) showed some remnants of the composite bonded to the abutment base. The ductile fractured cone area showed semielliptical lines, known as beach marks,[17] running perpendicular to the direction of fatigue crack propagation and marked two successive positions of the advancing crack front. A view of the mating half bottom of the fractured cone (Fig 7D) showed the matching features observed in the base of the abutment and a compression curl located opposite to the fracture origin, which is a significant sign that the specimen had a strong bending component.[25]

Discussion

This study evaluated the reliability and failure modes of indirect composites directly applied on titanium abutments of different dimensions for implant-supported single crowns. The rationale behind the use of abutments with varying base dimensions relies on the need for options to better fit the final crown in the different clinical scenarios of proximal distances within the edentulous areas being rehabilitated. In addition, shorter or longer cone heights are selected based on the occlusal clearance provided by the antagonist. The use level probability Weibull plots revealed that regardless of abutment configuration, failures were dictated by the material's strength and not fatigue damage accumulation. This behavior has been previously observed for implant-supported metal ceramic (FDPs).[21]

A retrospective cohort study of single implants restored with IACs™ followed up to 29 months, 71% being crowns restoring posterior areas (n = 59), showed one minor cohesive failure during the first year, and refinishing procedures allowed the crown to continue in function uneventfully for the remainder of the study. The survival rate was 98.7%, and color stability did not seem to be an issue affecting esthetics during this short-period evaluation.[26] In agreement with this failure mode, the magnitude of the fractures occurring within the range of maximal bite force in the molar area (approximately 500 N)[15,27] was also minor, as shown in our imaging results; however, failures occurring at higher load levels involved a larger area of the fatigued cusp. From a clinical perspective, these larger failures could still be repaired with an indirect composite and remain in function without the need of replacement.

The failure mode of the crowns was not related to abutment design. The different abutments provided different base support (LB compared to SB-2 and SB-4) and cone retention (LB and SB-4 compared to SB-2), resulting in more or less volume of

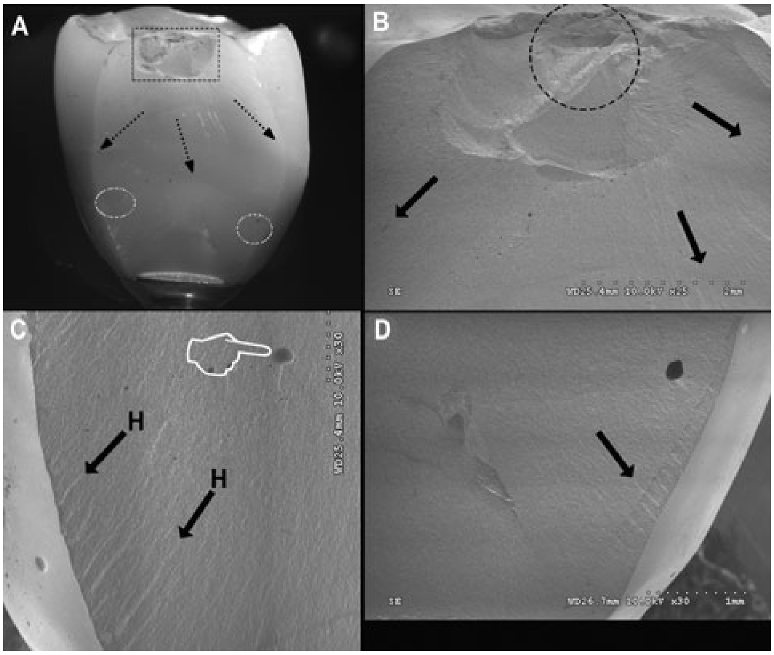

Figure 6 Cohesive failure within the composite of an SB-4 crown failed after 91,232 cycles at 800 N in the mild profile. (A) Polarized light micrograph shows the extension of the fracture and the indentation area (dashed rectangle) as the fracture origin. Note that a small area of the base of the titanium abutment was exposed. Fracture propagated toward the margins of cohesively failed composite (dotted arrows), leaving fractographic marks observed in detail in (B), where the SEM magnified view shows in greater detail the indentation area (dashed circle) and the direction of crack propagation (arrows). SEM micrographs (C) and (D) are magnified views of left- and right-dashed white circles shown in (A), respectively, where hackles (H, arrows) and wake hackles (pointer) portray crack front direction.

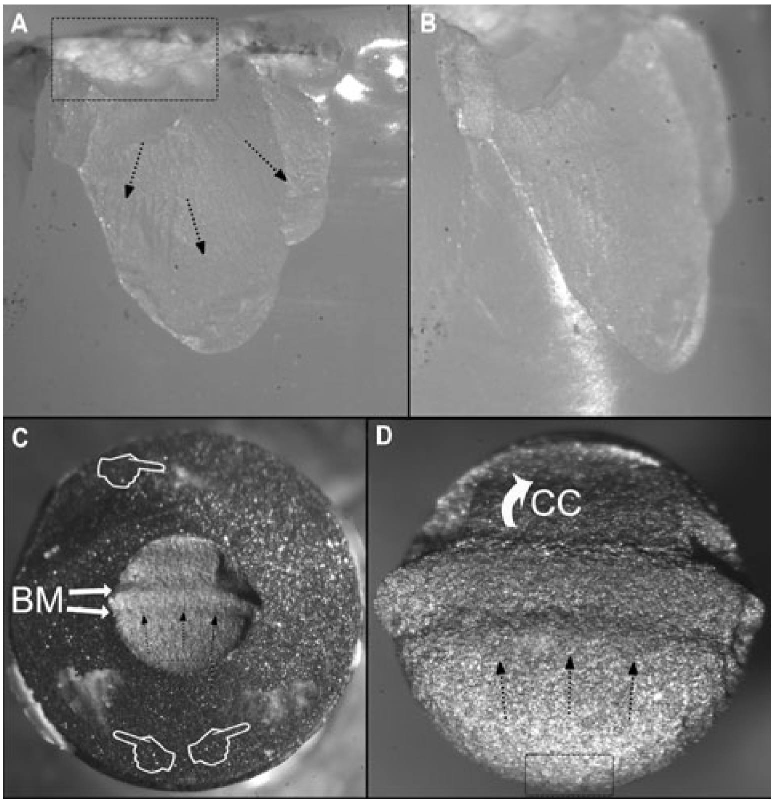

Figure 7 Composite chip of an LB crown failed after 71,132 cycles at 600 N in the mild profile. (A) is a polarized light micrograph of the chipped composite showing crack initiation site at the indentation area (dashed rectangle) and its propagation direction toward the margins of the fracture (dotted arrows). (B) is a profile view of the fracture showing its depth. (C) shows a ductile fracture of the base of the titanium cone at the abutment of an SB-4 crown after 113,157 cycles at 1000 N. Note that some indirect composite still remained bonded to the titanium base (pointer). Semielliptical lines, known as beach marks, are seen running perpendicular to the direction of fatigue crack propagation (dotted arrows). (D) is the magnification of the base of the fractured cone showing the matching features observed in (C), where the dashed rectangle indicates the fracture origin and the dotted arrows the direction of crack propagation. In addition, a compression curl is observed opposite to the fracture origin.

indirect composite being supported by the abutment, as imaged in the sectioned crowns. A few crowns (3 out of 18) of group SB-4 presented ductile fracture of the Ti cone, occurring at a 1000 N load. As observed in the fractographic analysis, the marks left on the Ti surface during the fracture showed indicators such as beach marks, which evidence failure origin and leave traces of the successive positions of the advancing crack front.[17] Since this failure mode was not observed in crowns of group LB, it is likely that such a high load level, while leading to a cohesive failure in the latter group, resulted in cone fracture in SB-4 due to the smaller base area for stress distribution. SB-2 crowns failed at lower load levels, the reason being that their characteristic strength, as observed in the probability Weibull contour plot, was significantly lower than groups LB and SB-4.

The increasing application and expansion in the use of indirect resin composites in dentistry is a result of innovations in materials and processing techniques.[28] Of special interest to the implant restorative field is the possibility that composites present significantly lower peak vertical and transverse forces transmitted at the peri-implant level compared to glass ceramic in implant-supported restorations.[29] The high reliability and repair-friendly failure modes observed for the crowns failed within and above the peak bite force range suggest that the use of indirect composites for implant-supported restorations warrants future clinical investigations. This study assessed the mechanical behavior of IACs™ under fatigue in water. Since aspects regarding the used indirect composite wear, potential use for fixed dental prostheses, surface degradation, plaque accumulation, and loss of surface gloss are not available, future well-designed clinical trials are also warranted to provide a thorough understanding of the long-term behavior of composites used as single-unit crowns for implant restorations. As to the loss of surface gloss, as well as the staining of composites, a recent publication evaluated several composites after artificial aging (thermocycling) followed by staining with coffee and wine. The spectrophotometric analysis showed that staining was as superficial as 20 μm and that polishing was able to reestablish the original color of the investigated composites.[30] Also, the use of a flat indenter could be seen as a possible drawback of this study, since mouth-motion sliding fatigue using a spherical indenter has been shown to simulate clinical failures on ceramic crowns.[22,23] Studies including this type of testing on implant-supported composite crowns are desired. Finally, future fatigue tests involving metal ceramic, known as the gold standard, as an implant-supported crown material are warranted to provide a sound database for comparison.

Conclusions

From a mechanical testing standpoint, our results showed that fatigue was not an acceleration factor for failure of the indirect resin composite applied to the different abutments, leading to acceptance of the first null hypothesis. Whereas fractographic analysis is a common practice in the ceramic field, it has often been neglected in mechanical property investigations of composites and has only recently been comprehensively described in bar-shaped dental resin specimens.[31] Telltale fractographic marks observed on ceramic surfaces that allow the determination of fracture origin and crack front propagation, such as hackles and wake hackles, were also identified on the fractured composite crowns, thus leading to rejection of the second null hypothesis.

Acknowledgments

This study was supported by FAPESP grant # 2010/06152-9, Brazil. Implants and abutments were generously provided by Bicon Dental Implants. The authors acknowledge Hitachi S3500N SEM imaging made possible by the New York University College of Dentistry's cooperative agreement with the NIH/NIDCR.

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