CLINICAL ORAL IMPLANTS RESEARCH

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Reliability and failure modes of internal conical dental implant connections

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Abstract

Objective: Biological and mechanical implant-abutment connection complications and failures are still present in clinical practice, frequently compromising oral function. The purpose of this study was to evaluate the reliability and failure modes of anterior single-unit restorations in internal conical interface (ICI) implants using step-stress accelerated life testing (SSALT).

Materials and methods: Forty-two ICI implants were distributed in two groups ($n = 21$ each): group AT–OsseoSpeed^{TM} TX (Astra Tech, Waltham, MA, USA); group SV–Duocon System Line, Morse Taper (Signo Vinces Ltda., Campo Largo, PR, Brazil). The corresponding abutments were screwed to the implants and standardized maxillary central incisor metal crowns were cemented and subjected to SSALT in water. Use-level probability Weibull curves and reliability for a mission of 50,000 cycles at 200 N were calculated. Differences between groups were assessed by Kruskal–Wallis along with Bonferroni's post-hoc tests. Polarized-light and scanning electron microscopes were used for failure analyses.

Results: The Beta (β) value derived from use level probability Weibull calculation was 1.62 (1.01–2.58) for group AT and 2.56 (1.76–3.74) for group SV, indicating that fatigue was an accelerating factor for failure of both groups. The reliability for group AT was 0.95 and for group SV was 0.88. Kruskal–Wallis along with Bonferroni's *post-hoc* tests showed no significant difference between the groups tested ($P > 0.27$). In all specimens of both groups, the chief failure mode was abutment fracture at the conical joint region and screw fracture at neck's region.

Conclusions: Reliability was not different between investigated ICI connections supporting maxillary incisor crowns. Failure modes were similar.

Since the definition and widespread application of the osseointegration principles, several designs for dental implant-abutment connection have been available for clinical use. Historically, the external hexagon connection was designed to provide an engagement method for implant placement and anti-rotational feature for single-unit prosthesis, and is likely the functioning system with longest clinical follow-up (Priest 1999; Scholander 1999; Wannfors & Smedberg 1999). The prerequisite for assembling an external hexagon abutment to an implant is the existence of a minimum space between engaging lateral walls of the implant connecting part and abutment internal surfaces. The resulting horizontal and rotational misfits under loading, especially in single-unit restorations lacking cross-arch stabilization, may present as a hindrance to the long-term stability and success of the implant-supported restoration (Binon 1996; Khraisat et al. 2002, 2004). Clinically, biological and mechanical implant-abutment connection complications and failures have been reported(Rangert et al. 1995; Esposito et al. 1998; Cardoso et al. 2010) and are of concern as they frequently compromise oral function and the psychosocial well being of patients.

As to the commonly observed mechanical failures, loosening and/or fracture of fixation screws or abutments have been related to the type of implant–abutment connection (Quek et al. 2008). Also of interest, from a biological perspective, is, that the microgap between implant and abutment may serve as a septic reservoir that initiates and perpetuates an inflammatory response with the potential to trigger peri-implantitis and play an important role in the multifactorial process of periimplant bone loss.(Hartman & Cochran 2004) In addition, micromovements of the implant

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and/or abutment, and periimplant vascular alterations might contribute to the influence of microbial contamination on the biologic width over time (Hermann et al. 2001; King et al. 2002). Therefore, improving the implant–abutment connection is of great interest for clinical longevity (Jung et al. 2008).

In an attempt to reduce the incidence of mechanical failures while improving the interface between soft tissue and implant-abutment junction, internal conical interface joint design (ICI connection) was developed. Different from external hexagon, the conical interface results in a relatively tight junction due to friction between implant and abutment (Bozkaya & Muftu 2003). It has been proposed to be more biomechanically stable than external or internal hexagonal implant–abutment connection.(Merz et al. 2000; Norton 2000; Steinebrunner et al. 2008) In the ICI connections, the form lock and friction are the basic principles and this mechanism, referred to as positive or geometric locking, is assumed to be responsible for shielding the abutment and fixation screw from loading (Merz et al. 2000). Thus, the reduced micro-movement of ICI connection should provide superior strength and joint stability (Merz et al. 2000). These potential mechanical advantages of internal conical joint design over internal and external hexagonal design were previously reported in *in vitro* (Merz et al. 2000) and *in vivo* (Levine et al. 1999; Mangano et al. 2009, 2011) studies. However, it is still unclear how the keying mechanism of ICI connections responds to fatigue testing, which was previously reported as an *in vitro* method able to reproduce clinical failures (Coelho et al. 2009a). Thus, the purpose of this study was to evaluate the reliability and failure modes of anterior single-unit restorations for ICI connection implants using step-stress accelerated life testing (SSALT) in water.

Materials and methods

Sample preparation

Forty-two Ti-6Al-4V ICI connection implants (~4.0 mm diameter by 11.0 mm length) were distributed in two groups ($n = 21$): group AT–OsseoSpeed^{TM} TX (Ref. # 24942; Astra Tech Inc., Waltham, MA, USA); group SV–Duocon System Line, Morse Taper (Ref. # 21223; Signo Vinces®, Campo Largo, PR, Brazil). All implants were vertically embedded in acrylic resin (Orthoresin, Degudent, Mainz, Germany), poured in a 25-mm-diameter plastic tube, leaving the top platform in the same level of the potting surface.

Following connection of the corresponding proprietary cement-retained abutment (group AT–Abutment TiDesign^{TM} 4.0, Ref. # 24285; Astra-Tech Inc.; and group SV–Anatomical Abutment, Ref. # 03111; Signo Vinces®) to the bearing housing, the titanium alloy abutment screws (group AT–Abutment Screw Design^{TM} 4.0, Ti-alloy, Ref. # 24449; Astra-Tech Inc.; and group SV–Screw, Ti-alloy, Ref. # 05306; Signo Vinces®) (Fig. 1) were tightened with a torque gauge (Nobel Biocare, Goteborg, Sweden) according to the manufacturer's instructions (20 N.cm). A maxillary central incisor crown was waxed to its close anatomical state and cast in a cobalt-chrome metal alloy (CoCr partial denture alloy, Wirobond® 280; BEGO, Bremen, Germany) with its cementation surface designed to fit the abutments from the first group (AT). To reproduce the anatomy of the first crown, an impression was taken from the first waxed pattern and used by the technician as a guide during waxing of crowns for the second group (SV). The cementation surface of the crowns was blasted with aluminum oxide (particle size ≤40μm, using 276 KPa compressed air pressure), cleaned with ethanol, dried with air free of water and oil, and cemented (Rely X Unicem, 3M ESPE; St. Paul, MN, USA) on the ICI abutments.

Mechanical testing and reliability analysis

For mechanical testing, the specimens were subjected to 30º off-axis loading. Three specimens of each group underwent single-load-to-fracture (SLF) testing at a cross-head speed of 1 mm/min in a universal testing machine (INSTRON 5666; Canton, MA, USA) with a flat tungsten carbide indenter applying the load on the lingual side of the crown, close to the incisal edge. Based upon the mean load to failure from SLF, three step-stress accelerated life-testing profiles were determined for the remaining 18 specimens of each group which were assigned to a mild ($n = 9$), moderate ($n = 6$), and aggressive ($n = 3$) fatigue profiles (ratio 3 : 2 : 1, respectively) (Nelson 1990; Nelson 2005; Coelho et al. 2009b). Step-stress loading 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, which means 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. 2) (Abernethy 2006).

The prescribed fatigue method was SSALT under water at 9 Hz with a servo-all-electric system (TestResources 800L; Shakopee, MN, USA) where the indenter contacted the crown surface, applied the prescribed load within the step profile and lifted-off the crown surface. Fatigue testing was performed until failure (bending or fracture of the fixation screw and/or abutment) or survival (no failure occurred at the end of step-stress profiles, where maximum loads were up to 800 N) (Nelson 1990; Nelson 2005; Coelho et al. 2009b). Use level probability Weibull curves (probability of failure versus cycles) with a power law relationship for damage accumulation were calculated (Alta Pro 7; Reliasoft, Tucson, AZ, USA) (Zhao 2005). The reliability (the probability of an item functioning for a given amount of time without failure) for a mission of 50,000 cycles at a 200 N load (Freitas et al. 2011)(Paphangkorakit & Osborn 1997) (two-sided 95% confidence intervals) was calculated for comparison between SV and AT. As the sample size utilized in the present investigation was small and the software utilized considers a z distribution for confidence bound construction, Kruskall–Wallis along with Bonferroni's *post-hoc* test at 95% level of significance was performed based on the load to failure of all samples tested under accelerate fatigue.

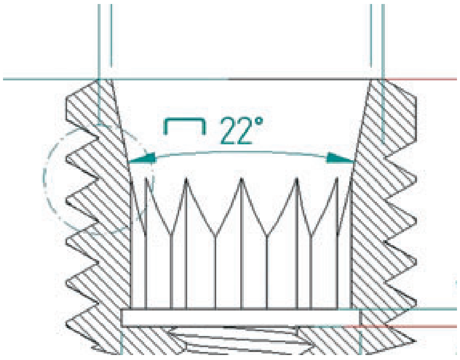

Fig. 1. Diagram depicting the internal conical interface angle for both implant systems.

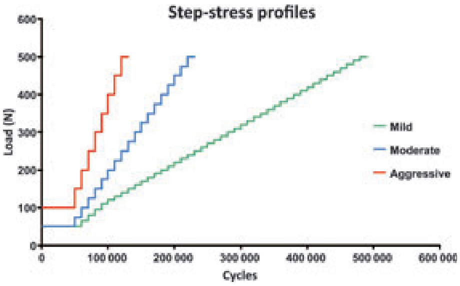

Fig. 2. This chart shows the mild, moderate, and aggressive load profiles used for accelerated fatigue testing of the internal conical interface implant systems.

Failure analysis

Macro images of failed samples were taken with a digital camera (Nikon D-70s; Nikon, Tokyo, Japan) and utilized for failure mode classification and comparisons between groups. To identify fractographic markings and characterize failure origin and direction of crack propagation, the most representative failed samples of each group were inspected first under a polarized-light microscope (MZ-APO stereomicroscope; Carl Zeiss MicroImaging, Thornwood, NY, USA) and then by scanning electron microscopy (SEM) (Model S-3500N; Hitachi, Osaka, Japan) (Parrington 2002; Manda et al. 2009).

Results

SLF and Reliability

The SLF mean ± standard deviation values for group AT were 430.17 N ± 50.22 N, and 468.8 N ± 25.15 N for group SV.

The step-stress derived probability Weibull plots and summary statistics at a 200 N load are presented in Fig. 3 and Table 1, respectively. The Beta (β) values and associated upper and lower bounds derived from use level probability Weibull calculation (probability of failure vs. number of cycles) of 1.62 (1.01–2.58) and 2.56 (1.76–3.74) for groups AT and SV, respectively, indicated that fatigue (damage accumulation) was an accelerating factor for failure in both groups.

The step-stress accelerated fatigue permit estimates of reliability at a given load level (Table 1). The calculated reliability with 95% confidence intervals for a mission of 50,000 cycles at 200 N showed that the cumulative damage from loads reaching 200 N would lead to implant-supported restoration survival in 95% of cemented restorations over AT implants, whereas 88% would survive in group SV when considering the given mission. Kruskal–Wallis along with Bonferroni's post-hoc tests showed no significant difference between the groups tested ($P > 0.27$).

Failure Modes

All specimens failed after SLF and SSALT. When component failures were evaluated together, failures comprised the combination of screw bending or fracture, and abutment bending or fracture. Failure modes for groups AT and SV are presented in Table 2.

Screw fracture at neck's region and abutment fracture at the conical joint region were the chief failure mode after SSALT for both groups (Fig. 4). In group AT, all the abutments presented complete fractures after SSALT, whereas the abutments were partially fractured in group SV. All implants were intact after mechanical testing.

Observation of the polarized-light and SEM micrographs of the fractured surface of screws (Fig. 5) and abutments (Fig. 6) allowed the consistent identification of fractographic markings, such as compression curl (the curved lip before total fracture of a body, indicating the existence of a strong bending component and that the fracture origin is on the opposite tensile side) (Quinn 2007) and beach marks (microscopic semielliptical lines running perpendicular to the overall direction of fatigue crack propagation and marking successive positions of the advancing crack front) (Parrington 2002), which allowed the identification of flaw origin and the direction of crack propagation.

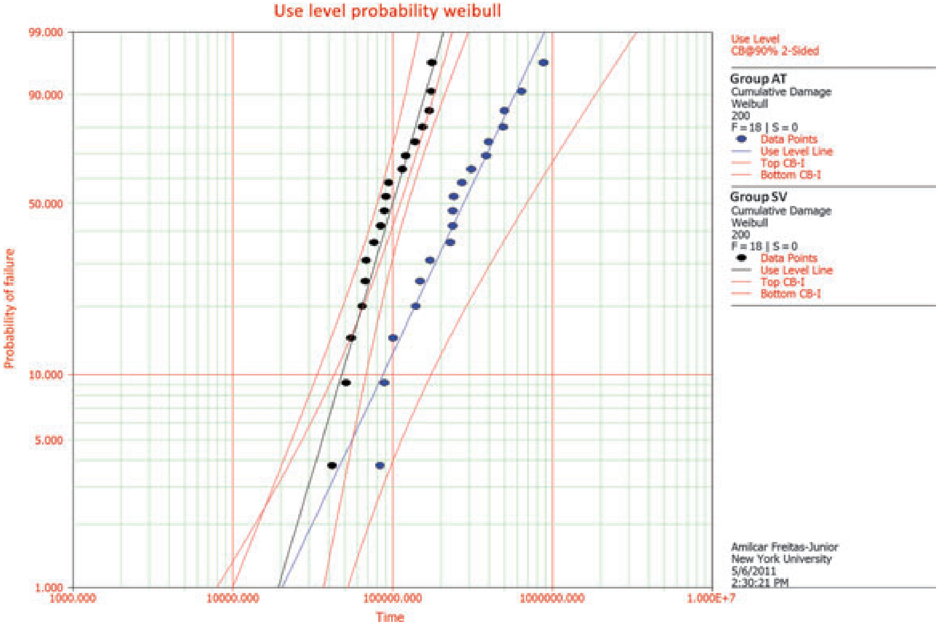

Fig. 3. Use Level Probability Weibull for groups AT and SV showing the probability of failure as a function of number of cycles (time) given a mission of 50,000 cycles at 200 N. Note that for each of the groups tested, the lowest data values tended to increase the slope of the Weibull fit. AT, Astra Tech; SV, Signo Vinces.

***Table 1.* Calculated reliability of anterior single-unit restorations for groups AT and SV given a mission of 50,000 cycles at 200 N load**

Output (50,000 cycles @ 200 N)	Astra Tech (AT)	Signo Vinces (SV)
Upper	0.98	0.95
Reliability	0.95	0.88
Lower	0.86	0.75

Discussion

Considering the relevance of a fatigue resistant implant-abutment connection for the long-term clinical success, the present study evaluated the reliability and failure modes of maxillary central incisor crowns restored with ICI implant abutments that are commercially available. The scenario simulated in the present study represented a common clinical situation for single-tooth replacements in anterior region of maxilla providing insight into the fatigue failure mechanisms involved in ICI connections. Thus, all specimens were subjected to step-stress accelerated fatigue test in water, which has been suggested as an important service-related cause of failure in metals (Parrington 2002). Our results showed that fatigue accelerated the failures of the two designs of ICI connections, as evidenced by the resulting β value (also called the Weibull shape factor): 1.62 (1.01–2.58) for group AT, and 2.56 (1.76–3.74) for group SV. The β value describes failure rate changes over time ($\beta < 1$: failure rate is decreasing over time, commonly associated with "early failures" or failures that occur due to egregious flaws; $\beta \sim 1$: failure rate that does not vary over time, associated with failures of a random nature; $\beta > 1$: failure rate is increasing over time, associated with failures related to damage accumulation) (Coelho et al. 2009b; Reliasoft 2010).

Given a mission of 50,000 cycles at 200 N load, our results showed no difference of fatigue endurance for both systems (AT and SV). In the present study, the region most susceptible to fracture was consistent (fracture at neck's region of the fixation screw, and fracture at the conical joint region of the abutments) regardless of the system used. In all specimens, the fractures were characterized

Table 2. **Failure modes after mechanical testing [single-load-to-fracture (SLF) and step-stress accelerated life-testing (SSALT)] according to the used failure criteria**

Groups	Astra Tech (AT)	Signo Vinces (SV)
SLF (*n* = 3)	Screw: 3 bending Abutment: 3 bending Implant: 3 intact	Screw: 3 bending Abutment: 3 bending Implant: 3 intact
SSALT (*n* = 18)	Screw: 18 fracture Abutment: 18 fracture Implant: 18 intact	Screw: 18 fracture Abutment: 18 fracture Implant: 18 intact

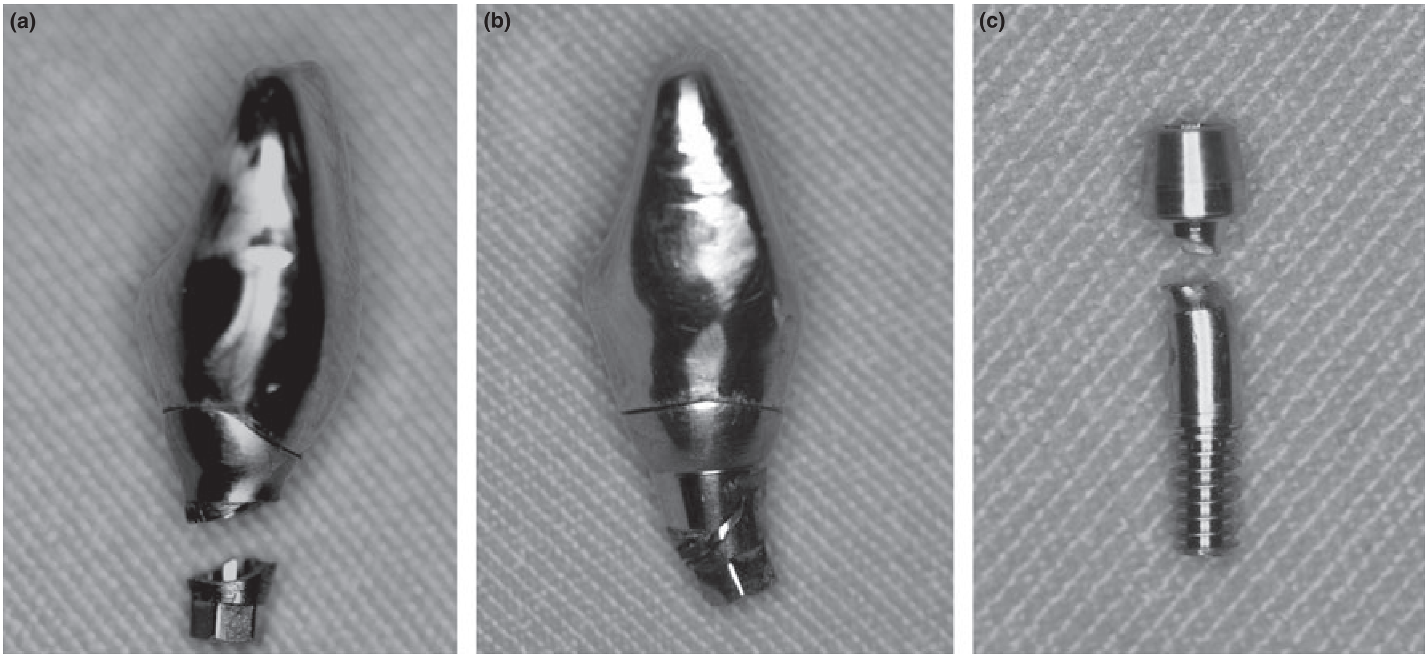

Fig. 4. Representative failure modes of single-unit implant-supported restorations observed in abutments and fixation screws after SSALT depicting: (a and b) A fracture occurring at the conical joint region of the abutments in groups AT and SV, respectively. (c) A fracture occurring at the screw's neck region in all tested specimens. SSALT, step-stress accelerated life-testing; AT, astra tech; SV, signo vinces.

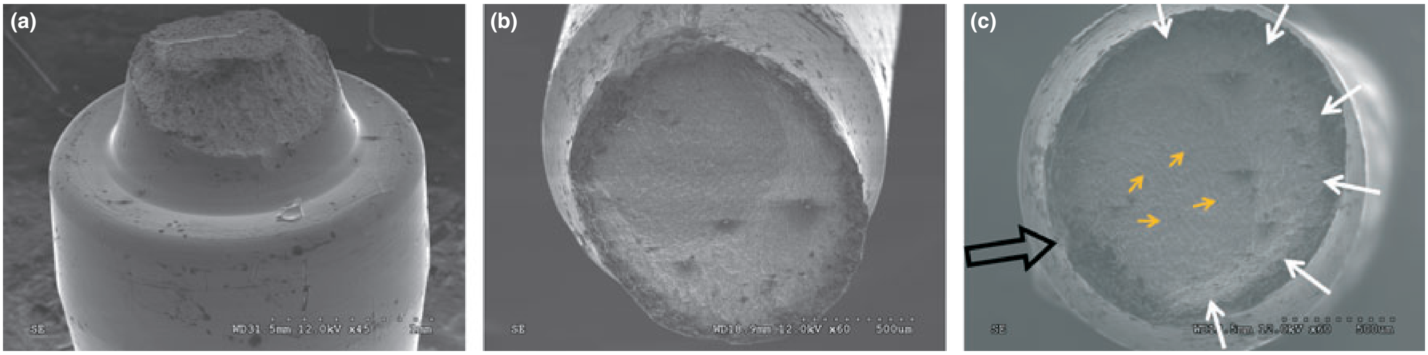

Fig. 5. (a and b) SEM micrographs of the upper and lower parts of fixation screw shown in Fig. 4c. (c) is a SEM micrograph of the fractured surface shown in (b). The white arrows show a compression curl, which evidences fracture origin at the opposing tensile side (larger black arrow). It is representative of flexure failures, and results from a traveling crack changing direction as it enters a compression field. Beach marks (yellow arrows), which are semielliptical lines running perpendicular to the overall direction of fatigue crack propagation and marking successive positions of the advancing crack front, are also observed indicating that crack propagated from lingual (fracture origin) to buccal (compression curl's region). SEM, scanning electron microscopy.

by material tearing and exhibited gross plastic deformation, suggesting ductile fractures (Parrington 2002). The ductile fractures as the result of stresses exceeding the material yield strength left marks indicating crack propagation from lingual to buccal, where occlusal forces naturally occur. In a study (Cehreli et al. 2004) in which the materials were fatigued under a constant load, no failures were observed in ICI connections (abutments and implants) after 500,000 cycles of 75 N. Conversely, in the present study, the materials were subjected to step-stress test to quickly yield failures. Thus, the tested model could properly take into account the cumulative effect of exposure at successive stresses and, consequently, the weakest point of ICI connections could be identified (Nelson 1990; Nelson 2005). On the other hand, another mechanical study (Perriard et al. 2002) compared a ICI connection with an octagonal internal key using the staircase technique to fatigue the specimens (maximum cycle number of 10^6) and observed that the location of the failure sites in ICI implant abutment group was distributed randomly across the structures (implant, abutment and fixation screw), thereby indicating the absence of locus of minor resistance on this connection.

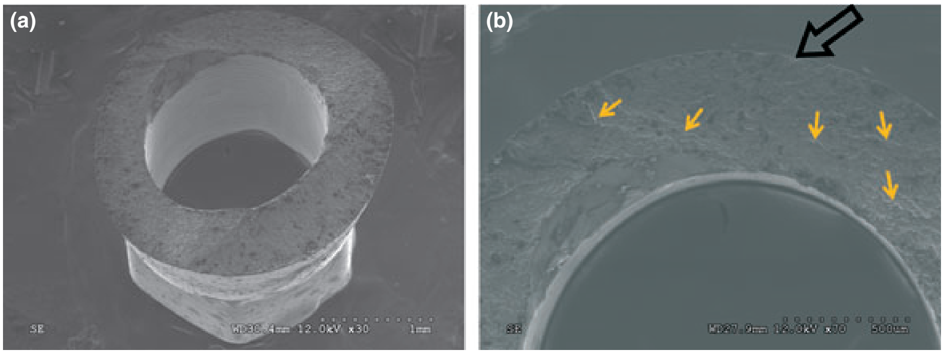

Fig. 6. (a) is a SEM micrograph of the lower part of internal conical interface abutment shown in Fig. 4a. (b) is a higher magnitude (70×) of sample shown in (a) illustrating the fracture origin (black arrow) and beach marks (yellow arrows) indicating direction of crack propagation from lingual to buccal. SEM, scanning electron microscopy.

As observed in maps of stress distribution from previous finite element analyses (Pessoa et al. 2010), the higher levels of stress are concentrated in the conical joint region of abutments when using ICI connection implant. These findings are in accordance with the chief failure mode observed in the present study. In addition, when compared with other connection designs, ICI connections present considerably lower stress concentration in the abutment screw than internal or external hexagon (Pessoa et al. 2010).

Considering that the replacement of single-unit edentulous spaces in the anterior region of maxilla with implant-supported restorations is a challenging scenario, it is crucial to acknowledge the functional and mechanical limitations of the implant-abutment connections. As the ICI connections have been assumed to be favorable in terms of long-term success and esthetics (Levine et al. 1999; Mangano et al. 2009, 2011), further evaluations of the implant-abutment stability combined with fatigue testing are warranted for this connection design and its variations. Fatigue testing in the posterior area with loading applied in more than one force vector is also warranted to assess the reliability of ICI connections. Furthermore, standardization of parameters adopted in mechanical tests is suggested to allow the comparison of reliability between different designs of ICI connections.

Conclusion

No differences in reliability values were observed for the two tested designs of internal conical interface connection. Fatigue (damage accumulation) was an accelerating factor for failure in both groups, and the chief failure mode was abutment fracture at the conical joint region and screw fracture at neck's region.

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