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Influence of platform diameter in the reliability and failure mode of extra-short dental implants

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ABSTRACT

Purpose: To evaluate the influence of implant diameter in the reliability and failure mode of extra-short dental implants.
Materials and methods: Sixty-three extra-short implants (5 mm-length) were allocated into three groups according to platform diameter: Ø4.0-mm, Ø5.0-mm, and Ø6.0-mm (21 per group). Identical abutments were torqued to the implants and standardized crowns cemented. Three samples of each group were subjected to single-load to failure (SLF) to allow the design of the step-stress profiles, and the remaining 18 were subjected to step-stress accelerated life-testing (SSALT) in water. The use level probability Weibull curves, and the reliability (probability of survival) for a mission of 100,000 cycles at 100 MPa, 200 MPa, and 300 MPa were calculated. Failed samples were characterized in scanning electron microscopy for fractographic inspection.
Results: No significant difference was observed for reliability regarding implant diameter for all loading missions. At 100 MPa load, all groups showed reliability higher than 99%. A significant decreased reliability was observed for all groups when 200 and 300 MPa missions were simulated, regardless of implant diameter. At 300 MPa load, the reliability was 0%, 0%, and 5.24%, for Ø4.0 mm, Ø5.0 mm, and Ø6.0 mm, respectively. The mean beta (β) values were lower than 0.55 indicating that failures were most likely influenced by materials strength, rather than damage accumulation. The Ø6.0 mm implant showed significantly higher characteristic stress (η = 1,100.91 MPa) than Ø4.0 mm (1,030.25 MPa) and Ø5.0 mm implant (η = 1,012.97 MPa). Weibull modulus for Ø6.0-mm implant was m = 7.41, m = 14.65 for Ø4.0 mm, and m = 11.64 for Ø5.0 mm. The chief failure mode was abutment fracture in all groups.
Conclusions: The implant diameter did not influence the reliability and failure mode of 5 mm extra-short implants.

1. Introduction

Dental implants have been used as a predictable therapy to restore missing teeth with high long-term implant survival rates associated with different prosthetic rehabilitations (Busenlechner et al., 2014). Nevertheless, reduced bone availability as a result of an extensive resorption process may hamper the placement of standard-length implants, specially in the posterior areas of the jaws due to the greater proximity to the inferior alveolar nerve and maxillary sinus (Jain et al., 2016). Additional surgical procedures such as bone regeneration, grafts, sinus lift, transposition of the dental nerve or the use of unconventional implants (tilted, zygomatic or transmandibular) may be necessary to reestablish the missing space (Asawa et al., 2015; Jain et al., 2016; Khojasteh et al., 2016; Lutz et al., 2015). These procedures are more complex, invasive, time-consuming and may add significant cost to the treatment (Jain et al., 2016).

Although there is no terminology consensus for implant length, a recently proposed classification scheme that will be used throughout this manuscript has suggested short implants to be more than 6 mm and less than 10 mm, and those of 6 mm or less of length have been classified as extra-short (Al-Johany et al., 2016). It has been reported that extra-short implants can be used as an alternative to avoid challenging

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surgical procedures, to reduce morbidity, and to further preserve important anatomic structures (Jain et al., 2016). Additionally, the cumulative survival rate varying from 98.1% to 99.7% after 7 years of follow-up are comparable to standard-length implants (Fugazzotto, 2008). The biomechanical concept involving extra-short implants relies on load bearing and stress dissipation chiefly confined to their cervical portion (first three to five threads) whereas the remainder of the implant length seems to contribute modestly to stress dissipation (Pierrisnard et al., 2003).

Since an increased interoclusal distance due to extensive bone resorption may result after tooth extraction, high crown-to-implant ratios can be experienced which may compromise the biomechanical behavior of extra-short implants (Quaranta et al., 2014). To overcome this problem, the use of wider platform extra-short implant diameters has been suggested (Sato et al., 2000). Previous studies have demonstrated that implant width is an important factor regarding treatment success (Moriwaki et al., 2016; Ortega-Oller et al., 2014). In addition, the wider the implant diameter, the higher the bone-to-implant contact in the cervical region resulting in stress distribution improvement in the cortical bone (Anitua et al., 2010; Brink et al., 2007; Himmlova et al., 2004). Also, the increase in bulk material in wider compared to narrower standard length implants typically results in a structural reinforcement that improves their capability to withstand higher fatigue loads (Song et al., 2016).

However, the information in the literature regarding the influence of width on the survival of extra-short implants is still controversial. A recent meta-analysis of prospective studies have evidenced that neither length nor width seemed to significantly affect the survival rate of short implants (< 10 mm), although the failure rates were reported to increase with increased short implant diameter (Monje et al., 2013). In contrast, a different meta-analysis showed that the failure rates of short implants were not affected by implant diameter (Pommer et al., 2011). Whereas it is clear that additional long-term clinical studies on short and extra-short implants are warranted, there is an inherent limitation in comparison between the existing trials considering that a variety of implant lengths, diameters, designs, prostheses types, and others are generally mixed during outcome report.

Although ideal, long-term clinical follow-up studies present high-costs and are time-consuming. Within this context, *in vitro* investigations, including fatigue testing may provide a fast screening of an implant system's overall performance and in some cases predict clinical outcomes (Bonfante and Coelho, 2016). Thus, the present study used step-stress accelerated life-testing (SSALT) to gain insight into the survival (reliability) and failure mode of extra-short implants with different diameters. Because of the time-varying stresses typically used in SSALT (3 stress profiles are commonly recommended) a cumulative damage model that best fits the data is chosen among Weibull, lognormal, and exponential (Nelson, 2004). The postulated null hypothesis was that extra-short implants with different diameter would not result in significant different reliability and failure mode.

2. Materials and methods

2.1. Sample preparation

Sixty-three commercially pure (grade IV) extra-short implants (5 mm-length) with internal conical configuration (Unitite Compact, S.I.N. Dental Implants System®, São Paulo, SP, Brazil) were selected and allocated into three groups (n = 21/group) according to the following implant diameters: ∅4 mm, 5 mm, and 6.0 mm.

All implants were vertically embedded into acrylic resin (Orthoresin, Degudent, Hanau-Wolfgang, Hessem Germany) which was poured into a 25 mm diameter polyvinil cloride tube (PVC). The implant's platform was positioned at the same level of the acrylic surface. Standardized crowns were waxed up and cast in a cobalt-chrome alloy (Wirobond 280, BEGO, Bremen, Germany). The crowns were cemented using a self-adhesive dual cure resin cement (Rely X Unicem, 3M Oral Care, St Paul, MN, USA)) onto prefabricated universal abutments (S.I.N. Dental Implants System®, São Paulo, SP, Brazil) previously tightened into the implants using a digital torque gauge (Tohnichi BTG150CN-S, Tohnichi America, Buffalo Grove, IL, USA) following the manufacturer's instruction (30 N.cm).

2.2. Mechanical testing

Three specimens of each group were subjected to single load-to-failure (SLF). A uniaxial compression load was applied at the incisal edge of the crown using a flat tungsten carbide indenter (6.25 mm diameter), 30° off-axis at a crosshead speed of 1 mm/min (Test Resources 800 L, Shakopee, MN, USA) (Almeida et al., 2013; Bonfante et al., 2015; Bordin et al., 2016; Freitas-Junior et al., 2012; Machado et al., 2013). The mean fracture load values were used to design the profiles for the step-stress accelerated life-testing (SSALT) (Bonfante and Coelho, 2016).

2.3. Step-stress accelerated life-testing (SSALT)

The remaining specimens (n = 18/group) were assigned into three step-stress profiles, mild (n = 9), moderate (n = 6) and aggressive (n = 3), following the aspect ratio distribution 3:2:1 (Bonfante and Coelho, 2016). The profiles were named based on the speed rapidness-increase in which a specimen would take to reach a certain load-level. For instance, a sample assigned to the aggressive profile is fatigued in less cycles to reach the same load level than a sample assigned to a mild profile.

SSALT was carried out on a servo-all-electric system (TestResources 800 L) under water at 9 Hz. The load was applied also at the incisal edge of the crowns with a flat tungsten carbide indenter, 30° off-axis. All samples were tested until failure (fracture or bending of the abutment or implant), or survival (no failure at the maximum 900 N load level) (Almeida et al., 2013; Bonfante et al., 2015; Bordin et al., 2016; Freitas-Junior et al., 2012; Machado et al., 2013).

Bending moment (M) and stress (σ) values were calculated as follow: $M = F.\,y$, where F is the loading force and y represents the moment arm (described as $y = sin30°.\,l$, in which l is the distance from the center of the hemisphere to the clamping plane); $\sigma_{Stress} = \frac{My}{I}$, where M represents the bending moment, y is the perpendicular distance from the center of the inertia moment and I is the area moment of inertia (described by the area of the abutment cross-section as $I_{circle} = \frac{\pi.d^4}{64}$, where d is the circle diameter). Findings were recorded as stress, number of cycles, and step-stress profile in which the specimen failed during accelerated life testing for the reliability calculations.

Then, use level probability Weibull curves (probability of failure (%) versus number of cycles) using a cumulative damage and power law relationship were calculated with use stress of 300 MPa at 90% two-sided confidence interval Synthesis 9, Alta Pro 9, Reliasoft, Tucson, AZ, USA). The reliability (probability of an item survive for a given mission was calculated considering 100, 200 and 300 MPa load at 100,000 cycles.

Additionally, the use level probability Weibull analysis provided the beta (β) value, which describes the failure rate behavior over time. If the use-level probability Weibull calculated β values were lower than 1 for any group, then a probability Weibull contour plot (Weibull modulus (m)) vs. characteristic stress (η) was plotted (Synthesis 9, Weibull ++, Reliasoft) using stress to failure or survival of groups (90% confidence intervals).

2.4. Failure analysis

Failed specimens were inspected under a polarized light microscope (MZ-APO Stereomicroscope, Leica, Buffalo Grove, IL, USA) and

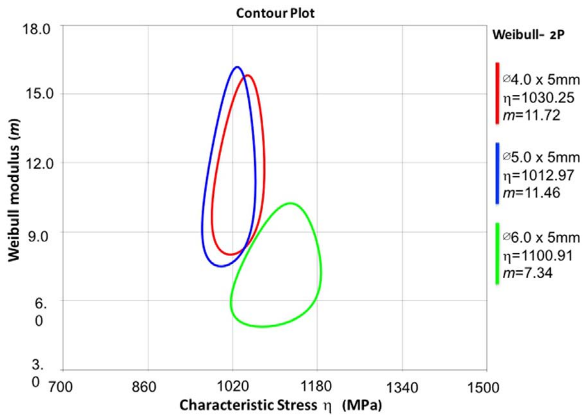

Fig. 1. Contour plot showing "*m*" as an indicator of structural reliability (Weibull modulus) vs. characteristic stress (η), which indicates the stress in which 63.2% of the specimens of each group may fail. The non-overlap between groups indicates significant difference.

evaluated through scanning electron microscopy (SEM) (S-3500N Hitachi, Germany) to analyze and classify failure modes.

3. Results

All samples failed after SSALT. Failures were restricted to abutment fracture. The mean β derived from the use-level probability Weibull were $\beta = 0.21$ for Ø4.0 mm, $\beta = 0.45$ for Ø5.0 mm, and $\beta = 0.55$ for Ø6.0 mm indicating that failures for all groups were dictated by material strength (egregious flaws) rather than damage accumulation.

The calculated Weibull modulus (*m*) and characteristic stress (η), which indicates the load in which 63.2% of the specimens may fail, are depicted in the contour plot (Fig. 1). Significant differences were identified considering the non-overlap of the contours. The ∅6.0 mm implant showed statistically higher characteristic stress ($\eta = 1100.91$ MPa) than ∅4.0 mm ($\eta = 1030.25$ MPa) and ∅5.0 mm ($\eta = 1012.97$ MPa). No difference was observed between ∅4.0 mm and ∅5.0 mm due to overlap between contours. Weibull modulus (*m*) for ∅4.0 and ∅5.0 mm implants was $m = 11.72$ and $m = 11.46$, and $m = 7.34$ for ∅6.0 mm (Fig. 1).

The use level probability Weibull (90% confidence bound) showing the probability of failure vs. number of cycles with stress at 300 MPa is shown in Fig. 2. The probability of survival, at a given mission of 100,000 cycles at 100, 200 and 300 MPa load is shown in Table 1. Statistical similarity was considered as the overlap of confidence bounds.

The cumulative damage from loads reaching 100 MPa resulted in probability of survival higher than 99% for all groups. An increase in stress to 200 MPA or 300 MPa decreased the reliability for all groups. The reliability at 300 MPa was 0% for both Ø4.0 and Ø5.0 mm implants, and 5.24% for Ø6.0 mm-diameter implant with no significant difference between groups.

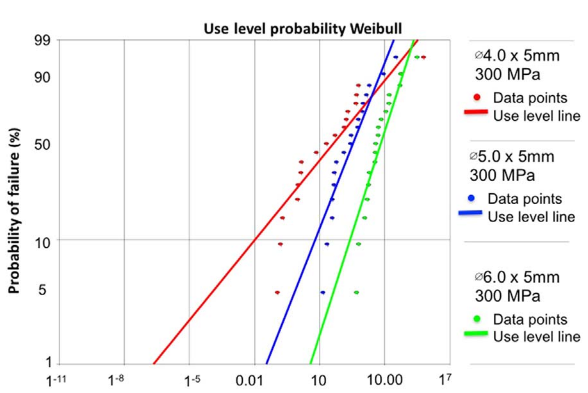

Fig. 2. Use level probability Weibull (90% confidence bound) showing the probability of failure vs. number of cycles for tested groups (set stress 300 MPa).

Table 1
Calculated reliability for a given mission of 100,000 cycles at a load of 100, 200 and 300 MPa. Different uppercase letters mean statistical difference between implant diameters. Different lowercase letters mean statistical difference between mission-load.

	∅4.0 × 5 mm	**∅5.0 × 5 mm**	**∅6.0 × 5 mm**
100,000 cycles at 100 MPa			
Upper bound	100%	100%	99.97%
Reliability	100% Aa	99.99% Aa	99.68% Aa
Lower bound	99.96%	99.78%	97.05%
Beta (β)		0.2528	
100,000 cycles at 200 MPa			
Upper bound	99.11%	96.01%	91.64%
Reliability	96.46% Aa	87.97% Ab	78.86% Ab
Lower bound	86.46%	66.79%	52.42%
Beta (β)		0.4526	
100,000 cycles at 300 MPa			
Upper bound	5%	1.84%	18.50%
Reliability	0% Ab	0% Ac	5.24% Ac
Lower bound	0%	0%	0.80%
Beta (β)		0.5574	

Fig. 3 shows the SEM of the fractured abutment. White asterisk represents the origin of the fracture at the surface subjected to tensile stress. When stress surpass the titanium strength, a plastic zone is created and the deformation process takes place. At the opposite surface, a rupture zone can be observed at the compression stress area.

4. Discussion

The postulated null hypothesis that extra-short implants with different diameter would not result in significant different reliability and failure modes was accepted. The results of this study indicate that from a mechanical perspective the implant diameter did not influence the probability of survival. Such results corroborate the high survival rates reported clinically for short implants (Annibali et al., 2012) in the sense that regardless of diameter and high crown-to-root ratios, several other factors seem to play a role in the longevity of restored short implants, such as type of connection, macrogeometry, and surface treatment (Monje et al., 2013; Pommer et al., 2011). The results are also encouraging considering that biting forces, as when chewing in the incisor region, is approximately 65 N (Kampe et al., 1987) to 100 N. (Fontijn-Tekamp et al., 2000)

Clinically, load bearing at posterior regions may range between 300 to 800 N, (Quiudini et al., 2016) and simulations performed herein should only be subjected to comparison to anterior regions given that samples were tilted 30° to impose a bending moment, whereas loading in posterior crowns results in axial loading. In addition, it is important to acknowledge that our findings are from fatigue testing and that positive biomechanical results still demand clinical trials to validate biological outcomes. In these regards, parameters such as reduced implant length and diameter should be compared with caution between industries since similar implant dimensions may present not only substantially different implant surface area, (Bozkaya et al., 2004) but also varied osseointegration healing modes and bone mechanical properties, due to variations in implant macrogeometry (Coelho et al., 2015).

Although the ∅6.0 mm group presented a slightly higher characteristic stress, it also resulted in the lowest Weibull modulus, reflecting a higher variability in strength. However, nominal stress values were high for all groups and differences between implant diameter groups were small and of questionable clinical relevance given that the abutment was the weakest link and only failing component within the restored system, and not the extra-short implant itself. In addition, the reliability calculations showed no differences between implant

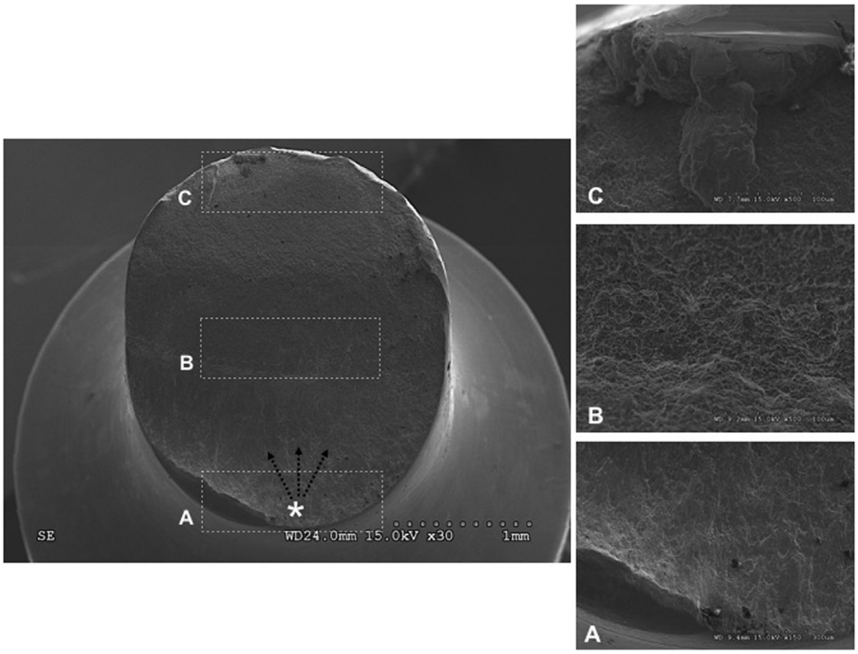

Fig. 3. Shows the fractured abutment. White asterisk represents the origin of the fracture at the surface undergone to tensile stress (A); black arrows indicate the crack propagation direction. When stress suppress the titanium strength, a plastic zone is created and the deformation process takes place (B). At the opposite surface, a rupture zone can be observed at the area subjected to compression stress (C).

diameters. Previous research has suggested that the wider the implant platform, the higher the abutment stress concentration (Anitua et al., 2010). From a biological standpoint, some studies have demonstrated that wider platforms provide greater bone-to-implant contact, which may be favorable to the osseointegration process (Anitua et al., 2010; Brink et al., 2007; Himmlova et al., 2004), Yet such observations may be interpreted with caution since survival of short implants was clinically shown not to be dependent on implant width (Monje et al., 2013). In contrast, wider platforms may also provide opportunities for increased implant-abutment mismatch, shown to be proportionally beneficial to peri-implant bone preservation in standard-length implants (Canullo et al., 2010). This information is yet to be confirmed for extra-short implants.

Although the clinical indication of extra-short implant platform width should be guided by both mechanical and biological aspects, ∅6.0 mm implants showed the highest characteristic stress, whereas this parameter was not different between ∅4.0 and 5.0 mm. However, the clinical significance of such finding may be questioned since the numerical differences between ∅6.0 mm and the other groups were only of approximately 60 MPa and most importantly, no differences in survival were observed between groups. Moreover, all groups showed $\beta < 1$, indicating that failures were attributed to materials egregious flaws rather damage accumulation, commonly associated with early failures (Bonfante and Coelho, 2016).

Extra-short implants may be a reasonable option for rehabilitation of severely reabsorbed bones, regardless of platform diameter, but long-term follow-up studies are mandatory. As of now, extra-short implants in areas with higher load and unfavorable crown-to-implant ratio have demonstrated better biomechanical performance when used as fixed partial prostheses and splinted crowns (Bal et al., 2013). For sound comparison in future studies, such implant designs, surface treatment, rehabilitation scenarios, and evaluation protocols should be standardized.

While widely used, it must be acknowledged that the Weibull distribution is a powerful statistical tool yielding parameters to be potentially used to relate test strength data to expected strengths for different stress configurations, specimen sizes, and testing conditions (Quinn and Quinn, 2010). Considering specimen size and assuming a symmetric largest flaw distribution, an inverse relationship between strength data and specimen size is commonly expected for brittle materials since smaller specimen sizes will present smaller flaw populations thus resulting in higher strength when compared to larger specimen sizes (Kotz, 2000). Our testing of extra-short dental implants implied in a reduced specimen size when compared to standard length implants, and a ductile rather than brittle failure mechanism typical of most ceramic materials. The validity of the statistical approach in terms of scaling the strength of ductile materials such as titanium in clinically relevant geometries, such as implants restored with crowns, should be explored in future studies.

5. Conclusion

The postulated null hypothesis that extra-short implants with different diameter would not result in significant different reliability and failure modes was accepted. Failures were restricted to abutment fracture for all groups.

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