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Fracture strength and probability of survival of narrow and extra-narrow dental implants after fatigue testing: *In vitro* and *in silico* analysis

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ABSTRACT

Purpose: To assess the probability of survival (reliability) and failure modes of narrow implants with different diameters.

Materials and methods: For fatigue testing, 42 implants with the same macrogeometry and internal conical connection were divided, according to diameter, as follows: narrow (Ø3.3×10 mm) and extra-narrow (Ø2.9×10 mm) (21 per group). Identical abutments were torqued to the implants and standardized maxillary incisor crowns were cemented and subjected to step-stress accelerated life testing (SSALT) in water. The use-level probability Weibull curves, and reliability for a mission of 50,000 and 100,000 cycles at 50 N, 100, 150 and 180 N were calculated. For the finite element analysis (FEA), two virtual models, simulating the samples tested in fatigue, were constructed. Loading at 50 N and 100 N were applied 30° off-axis at the crown. The von-Mises stress was calculated for implant and abutment.

Results: The beta (β) values were: 0.67 for narrow and 1.32 for extra-narrow implants, indicating that failure rates did not increase with fatigue in the former, but more likely were associated with damage accumulation and wear-out failures in the latter. Both groups showed high reliability (up to 97.5%) at 50 and 100 N. A decreased reliability was observed for both groups at 150 and 180 N (ranging from 0 to 82.3%), but no significant difference was observed between groups. Failure predominantly involved abutment fracture for both groups. FEA at 50 N-load, Ø3.3 mm showed higher von-Mises stress for abutment (7.75%) and implant (2%) when compared to the Ø2.9 mm.

Conclusions: There was no significant difference between narrow and extra-narrow implants regarding probability of survival. The failure mode was similar for both groups, restricted to abutment fracture.

1. Introduction

Implant therapy is a well-documented treatment for single, partial or full dental rehabilitations (Brugger et al., 2015). The long-term survival rates for this treatment modality range from 93.8% to 95.0% for implants and 89.5% for prostheses after 10 years of follow-up (Hjalmarsson et al., 2016). To achieve long-term success, implant's positioning requires at least 1 mm of residual bone adjacent to the implant platform, and 6 mm width horizontal alveolar crestal space in order to avoid biological complications. Also, 3 mm interimplant distance and 1.5 to 2 mm between tooth and implant seems to be adequate for papillary fill (Benic et al., 2012; Teughels et al., 2009).

Clinical complications, such as advanced bone resorption resulting from tooth extraction, where bone availability may be limited for standard platform implants (diameter ranging from 3.75 to 4.1 mm), commonly demand bone augmentation procedures prior to implantation. As a consequence, increased morbidity and healing-time is expected. In addition, grafting procedures may not be considered the first treatment option for elderly patients due to their general health risk factors. Also, additional appointments are required which increases treatment costs (Hattori et al., 2009; Walton and MacEntee, 2005; Zinsli et al., 2004).

Recently, the use of narrow diameter implants (NDI) (< 3.75-mm-diameter) has contributed significantly to the restoration of areas with limited prosthetic space and also, to avoid bone reconstructions (Andersen et al., 2001; Zinsli et al., 2004). It has been reported that

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approximately 10% of horizontal bone augmentation procedures could be avoided if NDIs were indicated (Papadimitriou et al., 2015). Prospective studies have presented promising data to support their use with similar survival rates to standard diameter implants (Arisan et al., 2010; Malo and de Araujo Nobre, 2011; Zinsli et al., 2004), and higher than 95% in a 11-year follow-up period (Malo and de Araujo Nobre, 2011).

However, rehabilitation of challenging scenarios as upper lateral and lower incisors can be problematic even with conventional NDIs. In order to manage different clinical scenarios, manufactures have started to offer NDIs with different diameters. Although there is poor consensus in the terminology used in the literature to categorize implants according to length and diameter, a recent study has proposed a classification system to overcome this issue. Narrow implants were subdivided into 2 main categories, as follows: implants with diameter of less than 3.0 mm were classified as extra-narrow, and with diameter equal to or more than 3.0 mm and less than 3.75 mm were classified as narrow implants (Al-Johany et al., 2016).

Extra-narrow implants typically feature a one-piece design that provides structural strength and also, simplifies treatment through flapless surgery. However, two-piece design is also available and provides a wider range of use due to a variety of prosthetic component options for rehabilitation.

Narrow-implants may experience increased fracture risk due to their smaller diameter that might compromise not only the prosthetic components but also lead to bone overloading (Allum et al., 2008). Abutment fracture has been reported as the primary prosthetic failure for two-pieces narrow implants (Bordin et al., 2016). The narrower the implant diameter, the smaller the stress distribution area, which could contribute to the implant itself being more prone to damage accumulation (Allum et al., 2008). It has been shown that from narrow to standard and large diameter implants an increasing probability of survival is observed with significant differences favoring cemented compared to screw-retained prostheses (Bonfante et al., 2015).

Considering that strength degradation of systems in function may steadily hamper their mechanical performance, fatigue testing of narrow dental implants becomes an important tool to understand the survival and failure of the implant-abutment-prostheses system (Almeida et al., 2013; Bonfante et al., 2015; Bonfante and Coelho, 2016; Freitas-Junior et al., 2012; Machado et al., 2013).

Therefore, the present study used step-stress accelerated life-testing (SSALT) to evaluate the probability of survival (reliability) and failure mode of extra-narrow (2.9 mm diameter) and narrow (3.3 mm diameter) dental implants. Finite element analysis (FEA) was also performed in order to measure the peak of stress concentration and compare with the fatigue findings.

The postulated null hypothesis was that narrow and extra-narrow implants would not present significantly different reliability and failure mode.

2. Materials and methods

2.1. Mechanical testing

2.1.1. Sample preparation

Forty-two 10 mm length dental implants with internal conical connections (commercially pure grade IV), (Unitite, S.I.N Implant system, São Paulo, SP, Brazil) were assigned to two groups according to implant platform's diameter: Ø2.9 mm, extra-narrow implant or Ø3.3 mm, narrow implant (n=21/group).

Implants were vertically embedded in polymethyl-methacrylate acrylic resin (Orthodontic resin, Dentsply, York, PA, USA) into a 25 mm diameter polyvinyl chloride tube (PVC) leaving the implant's platform positioned at the same level of the poured acrylic resin (ISO 14801:2007; Dentistry-Implants-Dynamic fatigue test for endosseous dental implants). Standardized monolithic abutments were torqued into the implants using a digital torque gauge (Tohnichi BTG150CN-S, Tohnichi America) following the manufacturer's instruction (30 N cm).

A standardized cobalt-chrome alloy (Wirobond 280, BEGO) maxillary central incisor crown was milled and cemented onto abutments using a self-adhesive dual-curing resin cement (Rely X Unicem, 3 M Oral Care, St. Paul, MN, USA).

2.1.2. Step-stress accelerated life-testing

Three specimens from each group were subjected to single load-to-failure (SLF) testing where an uniaxial compression load was applied 30° off-axis lingually at the incisal edge of the maxillary central incisor crown using a flat tungsten carbide indenter at a crosshead speed of 1 mm/min (Test Resources 800 L, Shakopee, MN, USA) following the ISO 14801:2007 (Dentistry-Implants-Dynamic fatigue test for endosseous dental implants) (Almeida et al., 2013; Bonfante et al., 2015; Freitas-Junior et al., 2012; Machado et al., 2013). The mean load to failure was used to design three stress profiles for the step-stress accelerated life-testing (SSALT). The remaining specimens (n=18/group) were assigned to the mild (n=9), moderate (n=6) and aggressive (n=3) stress profiles, following the aspect ratio distribution 3:2:1, as detailed elsewhere (Bonfante and Coelho, 2016). The results of the accelerated test were analyzed so that a profile of failure behavior was extrapolated to normal conditions (Bonfante and Coelho, 2016).

The SSALT was carried out on the same servo-all-electric system (TestResources 800 L) under water at 9 Hz until failure (considered as fracture or bending of the abutment or implant) or survival (no failure at the end of the step-stress profiles when testing was suspended) until a maximum load of 900 N (Almeida et al., 2013; Bonfante et al., 2015; Freitas-Junior et al., 2012; Machado et al., 2013).

Based upon the step-stress distribution of failures, the use-level probability Weibull curves (probability of failure (%) versus number of cycles) with a use stress load of 150 N at 90% two-sided confidence interval were calculated and plotted using a power law relationship for damage accumulation (Synthesis 9, Alta Pro 9, Reliasoft). The reliability was calculated for completion of a mission of 50,000 and 100,000 cycles at 50, 100, 150 and 180 N (90% two-sided confidence interval). The use level probability Weibull analysis provides the beta (β) value, which describes the failure rate behavior over time (Beta values < 1 indicates that failure rate decreased over time, Beta~1 failure rate does not vary over time; and $\beta > 1$ means that failure rate increased over time (Bonfante and Coelho, 2016).

The Weibull probability contour plot was used (Synthesis 9, Weibull ++, Reliasoft) to present final load to failure or survival of groups (90% confidence intervals). Weibull modulus [m] and characteristic strength [η] (load that 63.2% of the specimens of each group may fail) were identified for examining differences between groups based on the non-overlap of confidence bounds.

2.1.3. Failure analyses

All failed specimens were inspected under a polarized light microscope (MZ-APO Stereomicroscope, Leica MicroImaging, Thornwood, NY, USA) and classified according to the failure criteria. To identify failure origin and fractographic marks further scanning electron microscopy evaluation (SEM) (S-3500 N, Hitachi) was performed.

2.2. Finite element analysis

2.2.1. Models construction

A CAD software (SolidWorks- Dassault Systems) was used to create two 3D virtual models of a single implant restoration encompassing the implant's diameter platform: Ø2.9 mm and Ø3.3 mm. Implants' length (10 mm) and thread configuration (trapezoidal design) were standardized. A universal abutment (2.5 mm collar height) was concentric positioned into the implant and a cement-retained crown of a maxillary

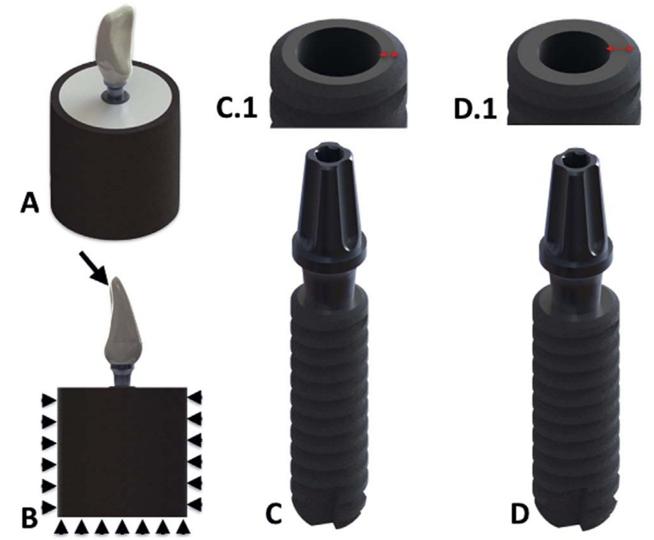

Fig. 1. shows the finite element models: A) Complete model embedded in the cylinder PVC tube. B) Black arrow indicates the load applied lingually at the incisal surface of the crown. Black triangles indicate the full constrain of the model. C and D show the 2.9 mm and 3.3 mm implant diameter, respectively. Red arrows show the difference between implant wall thickness. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

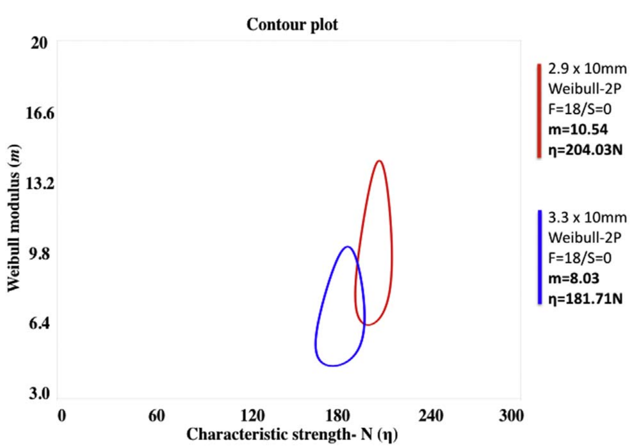

Fig. 2. Contour plot showing "m" as an indicator of reliability (Weibull modulus) vs. characteristic strength (η), which indicates the load in which 63.2% of the specimens of each group may fail. The overlap between groups indicates they are homogeneous.

central incisor was constructed based on the average dimensions of a natural teeth. A cement layer (60-µm-thick) was simulated in the interface between abutment and crown. The set was positioned into a virtual cylinder (Ø25 mm×20 mm) to simulate the same model of the *in vitro* analysis (Fig. 1).

2.2.2. Mathematical analysis

The models were imported by AnsysWorkbench to perform the mathematical analysis. A quadratic-tetrahedron element mesh was generated and refined manually. The materials properties Young modulus and Poison ration were: Titanium for implant, abutment and screw, 110 GPa 0.35 (Cruz et al., 2009); acrylic resin (2 GPa, 0.3) (Darbar et al., 1995) and PVC (1.43 GPa, 0.4) (Miniaci et al., 2015).

All models were considered homogeneous, isotropic and linearly elastics. All contacts were considered as bonded. Complete fixation (X, Y and Z axis) was applied at the lateral and lower surfaces of the cylindered model, following the same fixation that occurred during the *in vitro* test. Two different load profiles, 50 N and 100 N, were applied lingually at the incisal edge of the crown, 30° off-axis. The quantitative analysis was performed according to the von-Mises criteria for implant and abutment, while the qualitative analysis was performed following the stress distribution patterns.

3. Results

All specimens failed during SSALT testing. The mean beta (β) values (90% two-sided confidence interval) derived from use-level probability Weibull calculation were β=1.32 for Ø2.9 mm indicating that failures were likely dictated by damage accumulation and tended to increase overtime. In contrast the beta value of 0.67 for Ø 3.3 mm indicated that failures were likely dictated by material strength (egregious flaws) rather than damage accumulation.

The calculated Weibull modulus (*m*) and characteristic strength (η) are depicted in the contour plot (Fig. 2). Although higher characteristic strength and Weibull modulus values were found for Ø2.9-mm-diameter implant (η=204.03 N, *m*=10.54) when compared to Ø3.3-mm-diameter implant (η=181.71 N, *m*=8.03), there was no significant difference between them considering the overlap of the contours.

The calculated reliability with 90% confidence intervals for missions of 50,000 and 100,000 cycles at 50 and 100 N showed that the cumulative damage from loads reaching 50 and 100 N would keep the probability of survival higher than 97% for both implant diameters (Table 1). When the load was increased to 150 N, a significant decrease in reliability for both implant groups was detected. The probability of survival after 100,000 cycles at 150 N was 61.5% and 26% for Ø2.9 and Ø3.3 mm implants, respectively, with no significant difference between groups considering the overlap of confidence bounds. At 180 N, for missions of 50,000 and 100,000 cycles, both implant diameters showed 0% of reliability.

SEM images (Fig. 3) showed that fracture initiates where the loading condition caused a local tensile stress at lingual surface located in the abutment collar level (origin of the fracture). The stress exceeded the strength of material creating a plastic zone due to titanium ductile behavior. Plastic deformation was observed and the fracture propagated to the opposite side of the origin.

Table 2 shows the von-Mises stress (MPa) for abutment and implant considering implants diameter and loading conditions.

Table 1
Calculated reliability (%) for a given mission of 50,000 and 100,000 cycles at a load of 50, 100, 150 and 180 N.

		50 N		100 N		150 N		180 N	
		Ø2.9-mm	Ø3.3-mm	Ø2.9-mm	Ø3.3-mm	Ø2.9-mm	Ø3.3-mm	Ø2.9-mm	Ø3.3-mm
50,000 cycles	Upper bound	100	100	100	99.6	92.4	64.0	20.0	7.0
	Reliability	100	100	99.9	98.46	82.3	42.8	2.0	0
	Lower bound	100	99.9	99.5	93.0	61.8	19.9	0	0
100,000 cycles	Upper bound	100	100	100	99	84.4	55.4	7.0	4.0
	Reliability	100	100	99.9	97.5	61.5	26.0	0	0
	Lower bound	100	99.9	99.1	89.4	24.8	4.8	0	0

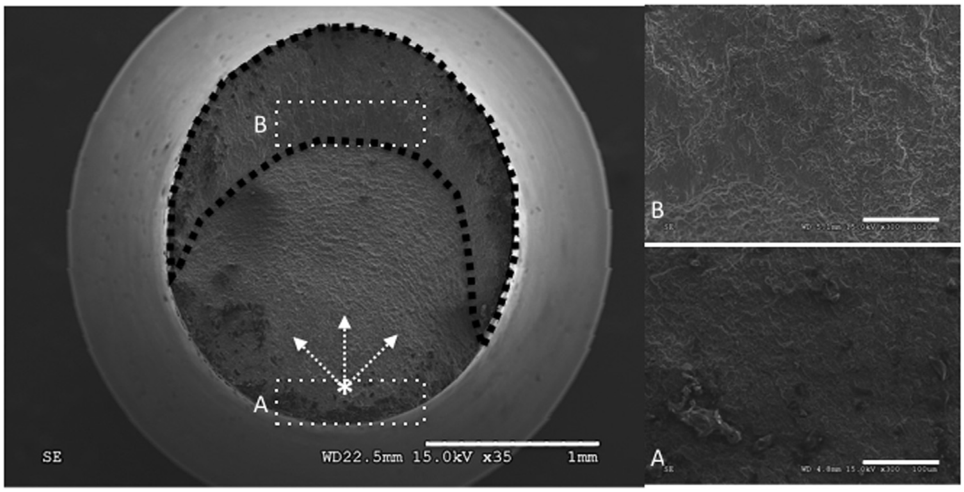

Fig. 3. Overall image of a fractured sample (35× magnification). Black dashed-line delimits dimple structure, typically observed in the end of fracture of ductile materials. At 300× magnification: 3.A) Fracture origin (white asterisk) where the surface underwent to tensile stress. The dashed-withe arrows indicate the direction of crack propagation. 3.B) Rupture zone (compression stress).

Table 2
Von-Mises stress for implant and abutment (MPa) according to implants' diameter and loading conditions. The difference between models was calculated in percentage (%).

	50 N			100 N		
	∅2.9-mm	∅3.3-mm	Difference	∅2.9-mm	∅3.3-mm	Difference
Implant	329.66	336.5	2%	659.33	673	2%
Abutment	455.17	493.46	8%	910.34	986.92	8%

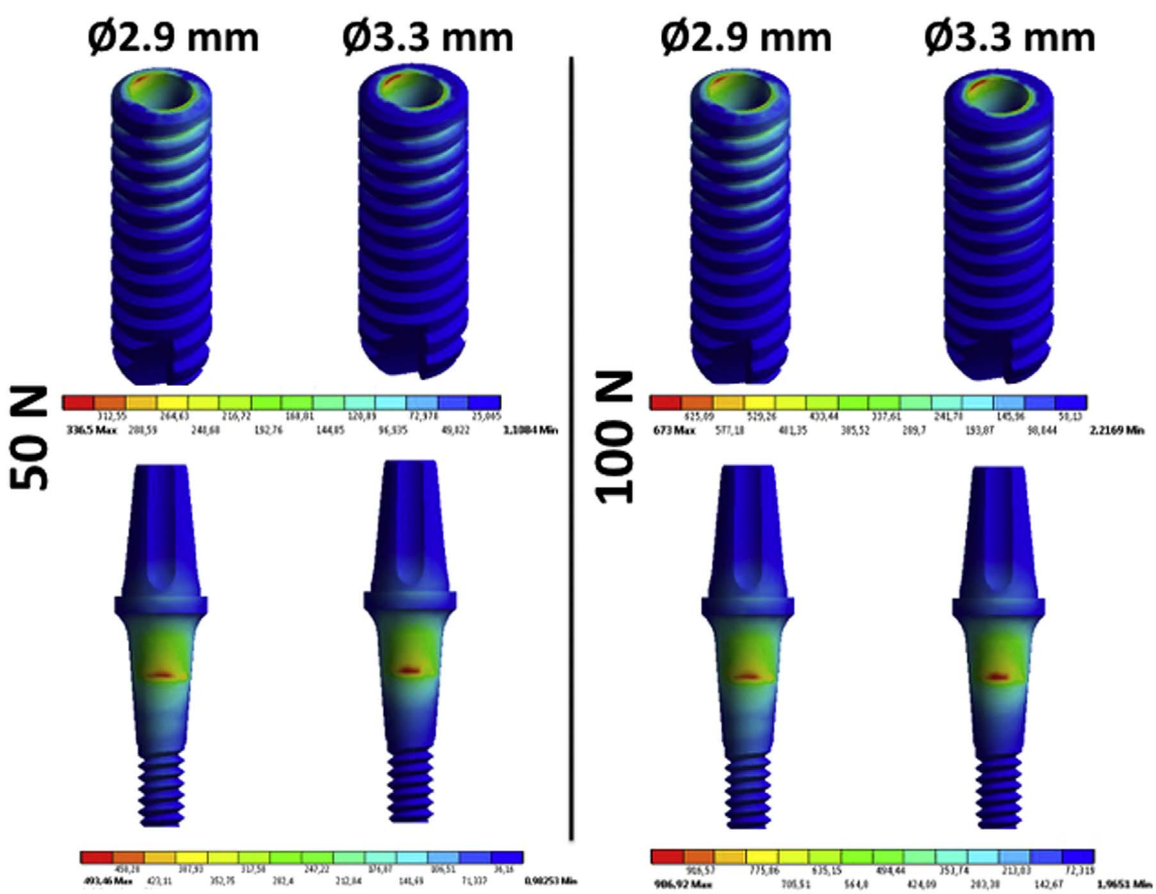

Fig. 4. Stress peak concentration for both implants diameter at 50 and 100 N loading. A similar stress behavior was observed regardless implant diameter and loading condition.

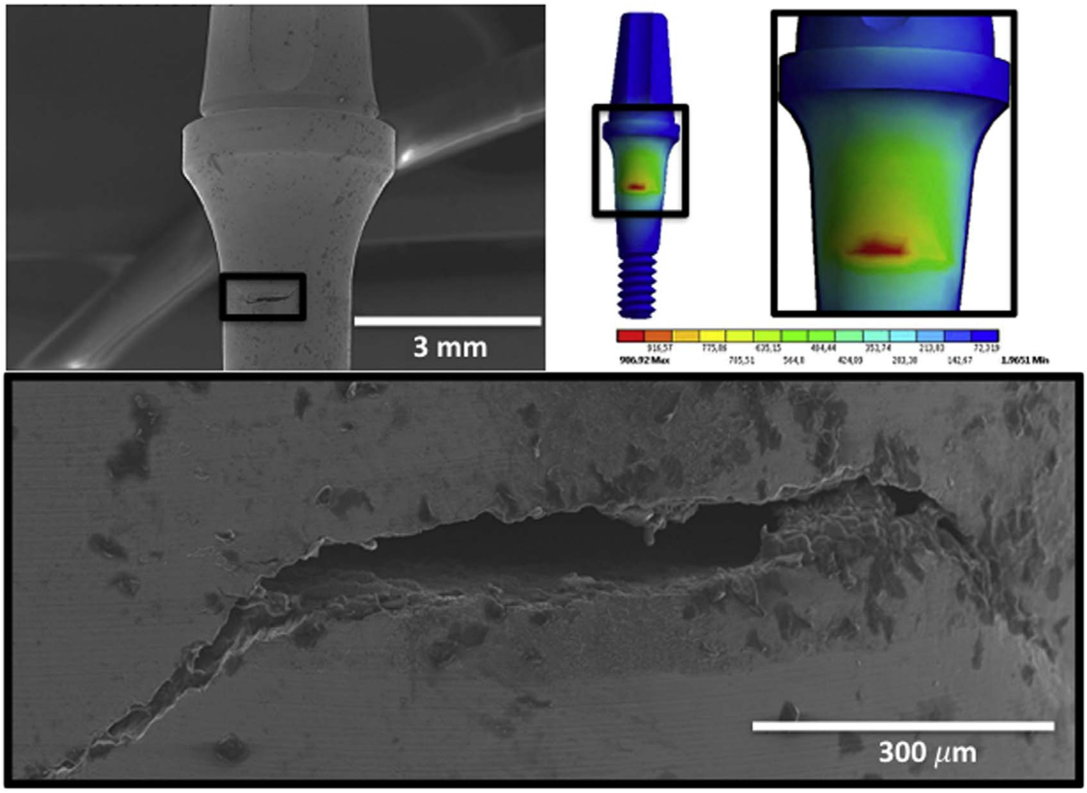

Fig. 5. A and B) SEM images show the beginning of the fracture in the lingual surface of the abutment underwent to tensile stress. C). Von-Mises stress peak concentration comparable to the SEM findings.

A similar stress distribution was observed regardless of implant diameter or loading condition. The peak stress concentration was located in the implant walls and in the abutment collar in contact with implant (Fig. 4).

At 50 N and 100 N load, the use of Ø3.3 mm implants increased up to 8% the stress concentration at the abutment and the peak stress was concentrated at the collar level in contact with implants internal walls. A load increase to 100 N generated greater stress concentration for all models. Fig. 5 shows damage created during fatigue that generated the initiation of the fracture on the lingual surface of the abutment, which underwent tensile stress after oblique loading (30° off-axis). The Von-Mises stress peak concentration in the virtual abutment model was comparable to the SEM findings.

4. Discussion

The postulated null hypothesis, which stated that restored narrow and extra-narrow implants would not result in different reliability and failure mode, was accepted. Both groups showed similar probability of survival for all missions. At a given mission of 50 N and 100 N, both groups evidenced probability of survival higher than 97%. This data suggests that both implant diameters can be a reliable option to replace incisors and premolars since mean bite forces in these regions vary within the cited range (Hattori et al., 2009). However, a decreased probability of survival was observed at 150 N and at 180 N when the values were 0% with no difference between groups. Obviously, if one considers maximum voluntary bite force values, most standard diameter implant-supported reconstructions may be at risk, especially in the molar region (Bonfante and Coelho, 2016; van der Bilt, 2011). Finite element analysis also showed an increased stress concentration for abutment and implant as the applied load increased. Therefore, considering that bite forces in the posterior region are increased, (Abe et al., 2012) and that the failure rates of prostheses are also increased when compared to the anterior region (Goodacre et al., 2003), implants with larger diameter may be better indicated to avoid mechanical complications.

Fatigue accelerated the failure of Ø2.9 mm implant, while the failures of Ø3.3 mm group were attributed to material egregious flaws rather than fatigue. Although Ø2.9 mm implant has shown higher characteristic strength and Weibull modulus than Ø3.3 mm, there was no significant difference between groups. Weibull modulus (m) is used as an indicator of strength survival and/or asymmetric strength distribution as a result of flaws presence within material structure. Higher m values, as slightly evidenced in the 2.9 mm diameter implants, indicates a more homogeneous flaw size distribution, less data scatter, and greater structural reliability (Quinn and Quinn, 2010; Ritter, 1995).

Finite element analysis showed that Ø3.3 mm implant tends to concentrate higher stress level at the abutment surface than Ø2.9 mm. A potential explanation is the thicker walls of narrow relative to extra-narrow implants, which provides an improved structural reinforcement. Nevertheless, it is important to highlight that extra-narrow implants may result in higher stress peaks at the bone-implant interface than narrow and standard diameters due to its reduced bone-to-implant contact area. The higher the stress peaks at the implant-bone interface, the greater the susceptibility to peri-implant crestal bone resorption (Klein et al., 2014).

Results from a recent systematic review evidenced that extra narrow implants (< 3 mm) presented higher bone loss when compared to conventional narrow implants (3.0 mm to 3.5 mm), and the authors reported that extra-narrow implants would be indicated only to the edentulous arch and nonloaded anterior region (Klein et al., 2014). However, it is important to acknowledge that implants included in this review were one-piece, had a diameter of 1.8, 2.4 or 2.5 mm and in most cases, were used to immediately load overdentures with survival rates between 90 and 100%. It is evident that, whereas highly positive for survival rates, such results for bone loss cannot be extrapolated for comparison with our study since the extra-narrow implants we have tested were of 2.9 mm diameter, two-piece, and indicated for loaded anterior regions. Thus, whether extra-narrow implants of 2.9 mm may present bone loss as reported for implants of 1.8, 2.4 and 2.5 mm remains to be investigated.

For both implant diameters, failure predominantly involved abutment fracture with no implant failure. This fact suggests that the friction-locking system of internal conical implant-abutment connection, which extends the contact of the abutment with the implant internal walls, protects the implant even in extra-narrow diameter implants (Almeida et al., 2013; Merz et al., 2000). Due to the analysis of failed prosthetic components it was possible to identify the fracture origin and the direction of crack propagation. The fractures showed a consistent crack pathway from lingual to buccal, where forces naturally occur and as simulated in the present study. Additionally, the von-Mises stress criteria, which is commonly associated with fatigue behavior of ductile materials, evidenced stress peak concentration compatible with the mechanical test.

No significant differences were observed between narrow and extra-narrow implants in probability of survival, failure modes, and characteristic strength. Whereas these findings are encouraging, given that indication of these implants may benefit patients in avoiding bone-grafting procedures and in extending the range of indication, they certainly demand validation in future clinical trials. Also, because mechanical testing was limited to single restorations, such assumptions are yet to be confirmed for fixed dental prostheses or full arch reconstructions, where units are splinted.

5. Conclusion

The postulated null hypothesis, which suggested that narrow and extra-narrow implant diameter would not result in different reliability and failure mode, was accepted. The results of *in silico* analysis were comparable to the *in vitro* test.

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