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Fatigue Failure of Narrow Implants with Different Implant-Abutment Connection Designs

Dimorvan Bordin, DDS, MSc,[1,2] Lukasz Witek, MSc, PhD,[2] Vinícius P. Fardin, DDS, MSc,[3]
Estevam A. Bonfante, DDS, MSc, PhD,[3] & Paulo G. Coelho, DDS, PhD[2,4]

[1]Prosthodontic and Periodontology Department, Piracicaba Dental School, University of Campinas, Piracicaba, Brazil
[2]Department of Biomaterials and Biomimetics, College of Dentistry, New York University, New York, NY
[3]Department of Prosthodontics, Bauru College of Dentistry, University of São Paulo, Bauru, Brazil
[4]Hansjörg Wyss Department of Plastic Surgery, New York University School of Medicine, New York, NY

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Correspondence
Paulo G. Coelho, Department of Biomaterials and Biomimetics, College of Dentistry, New York University, 433, 1st Ave, Room 844, New York, NY 10010. E-mail: pgcoelho@nyu.edu

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Abstract

Purpose: To evaluate the reliability of narrow diameter dental implants (NDIs) with similar macrogeometry and 3 implant-abutment connection designs.
Materials and Methods: Eighty-four NDIs (3.5 × 10 mm) were selected and divided into 4 groups ($n = 21$/group) according to implant-abutment connection design, as follows: EH – external hexagon, IH – internal hexagon, IC – internal conical, and IC-M – internal conical connected to a monolithic titanium abutment. 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. Use of level probability Weibull curves, and reliability for a mission of 50,000 cycles at 75 N and 200 N were calculated.
Results: The beta (β) values were: 1.48 for IC, 1.40 for IC-M, 8.54 for EH, and 1.98 for IH, indicating that damage accumulation was an acceleration factor for failure of all groups. At 75 N the probability of survival was not significantly different between groups. A decrease in reliability was observed for all groups at 200 N with no significant differences between IC (81.71%) and IC-M (94.28%), or between EH and IH (0%) which presented the lowest values. EH failures were primarily restricted to the screw, while IH involved screw and implant fracture. IC and IC-M were restricted to prosthetic failures (fracture and bending).
Conclusions: Narrow implants with external or internal hexagon connections presented the lowest reliability at high loads compared to internal conical connections. Failure modes differed among connections.

High clinical survival rates have been reported for single and full-arch restorations using standard-diameter dental implants, which range from 3.75 to 4.1 mm.[1,2] However, for clinical scenarios including narrow ridges, commonly present in anterior regions as a result of bone resorption, reduced interdental space after orthodontic therapy or missing lateral incisors,[3,4] the surgical installation of standard platform implants may not be possible without bone grafting procedures. Several reports suggest the need of a minimum residual bone space of 1.5 to 2 mm between a tooth and an implant and of approximately 3 mm between implants to accommodate tissues and adjacent structures for proper function and esthetics.[5-7] Additionally, the reduced thickness of residual marginal bone (<1.8 mm) increases the probability of biological complications.[7]

To restore such challenging clinical scenarios, narrow diameter dental implants (NDIs) ($\varnothing < 3.5$ mm) can be a viable option to avoid additional surgical procedures as in horizontal bone augmentation, which increases healing time, cost, and morbidity.[8] The use of NDIs between 3.3 and 3.5 mm has shown survival rates between 88.9% and 100%, which are not different from standard diameter implants.[4] Therefore, this treatment modality may be especially beneficial to the elderly or patients with compromised medical conditions, as it may reduce the number of interventions throughout the rehabilitation process.[3,4,8,9] Although several studies have reported survival rates greater than 89% after a 5-year follow-up,[1,9] concerns regarding NDIs' longevity have been raised due to their applicability in demanding clinical scenarios.[10,11] Considering that the varied implant-abutment connection geometries affect the performance of standard diameter implants,[12-14] it seems reasonable to hypothesize that the reduced material bulk in NDIs may proportionally hamper long-term function, which is yet to be investigated. Their small diameter and reduced wall thickness can result in an increased bending of the prosthetic components and consequently compromise the restoration's reliability.[10,15,16]

Mechanical complications have been reported to increase when external hexagon (EH) connections are used, due to their instability and reduced resistance to oblique loads.[12] In an attempt to improve their reliability, internal connections such as internal hexagon (IH) or internal conical (IC) connections are used in an attempt to shield the abutment screw from mechanical overloading.[12] However, even in screwed IC connections, relatively frequent abutment neck fractures have been reported in a long-term clinical study, concurrent with screw fractures and some involving implant fractures.[17] Therefore it must be acknowledged that whereas improved performance is anticipated in screwed IC connections, the relatively thin abutment walls seem susceptible to failure, considering the expected long-term role of fatigue in the strength degradation of prostheses.[18] As an alternative, the use of monolithic or full-contour abutments connected to internal conical implants have been in use with allegedly higher performance when compared to conventional two-piece abutment and screw restorations.[10] This assumption warrants further investigation, especially in a scenario such as NDIs where competing failure modes are likely to take place between thin implant walls and conventional abutments and screws.

This study sought to evaluate the failure modes and probability of survival (reliability) of NDIs using different implant-abutment connection designs subjected to step-stress accelerated life testing (SSALT). The first postulated hypothesis stated that the implant's connection type would result in different failure modes and reliability values. The second hypothesis stated that the monolithic abutments in the internal conical connection would result in higher reliability compared to the other groups.

Materials and methods

Specimen preparation

Eighty-four (n = 84) commercially pure titanium (Cp grade 2) NDIs (Ø 3.5×10 mm; Implacil de Bortoli, São Paulo, Brazil) were assigned into four groups (n = 21/group) according to implant-abutment connection design and abutment type as follows: (EH) – external hexagon, (IH) – internal hexagon, (IC) – internal conical, (IC-M) – IC internal conical implant connected to monolithic abutments. Figure 1A shows the all connections tested.

All implants were vertically embedded in an acrylic resin (Orthoresin; Degudent, Hanau-Wolfgang, Germany) and plastic tube (Ø25 mm × 35 mm) with the implant's platform positioned at the same level of acrylic resin. Maxillary central incisor crowns were standardized, waxed up, and cast in a cobalt-chrome alloy (Wirobond 280; BEGO, Bremen, Germany). The respective abutments were connected to the implants and tightened using a digital torque gauge according to manufacturer's instructions. Prior to the cementation procedure, crowns were cleaned with 100% ethanol and dried with oil-free air spray. Afterwards, crowns were cemented with self-adhesive dual-curing resin cement (Rely X Unicem; 3M Oral Care, St. Paul, MN).

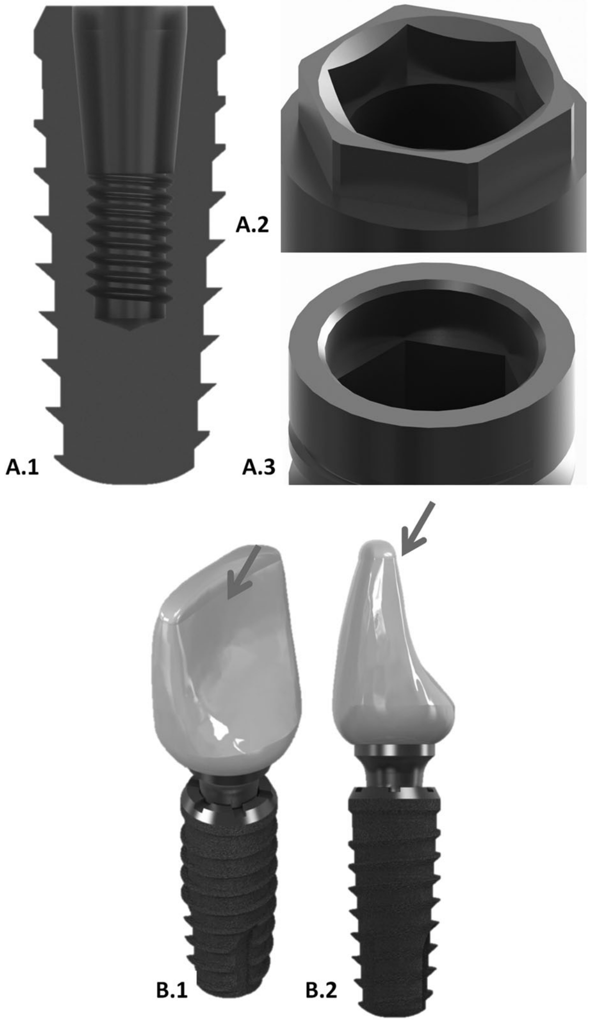

Figure 1 Implant connections tested: (A.1) IC-internal conical. (A.2) EH-External Hexagon. (A.3) IH-Internal Hexagon. (B) A representative image of load application (30°) lingually at the incisal edge of the crown during step-stress accelerated life-testing (SSALT), from an isometric view (B.1) and lateral view (B.2).

Mechanical testing

Three specimens from each group underwent single load to fracture (SLF) testing in a 30° off-axis loading universal testing machine (TestResources 800L, Shakopee, MN). A single compression load was applied lingually, at the incisal edge of the crown using a flat tungsten carbide indenter at a 1 mm/min crosshead speed until fracture (Fig 1B). Based upon the mean load of fracture, three fatigue loading profiles were designed for the 18 remaining specimens to undergo SSALT. The designed profiles were named as mild (n = 9), moderate (n = 6), and aggressive (n = 3), on the ratio distribution of 3:2:1.[18] These profiles were named primarily on the gradual increase-load rapidness that each specimen was tested to reach a certain level of load. Therefore, a specimen subjected to the mild profile took a longer time (cycles) to reach the same load level in comparison to the moderate or aggressive profiles.[18]

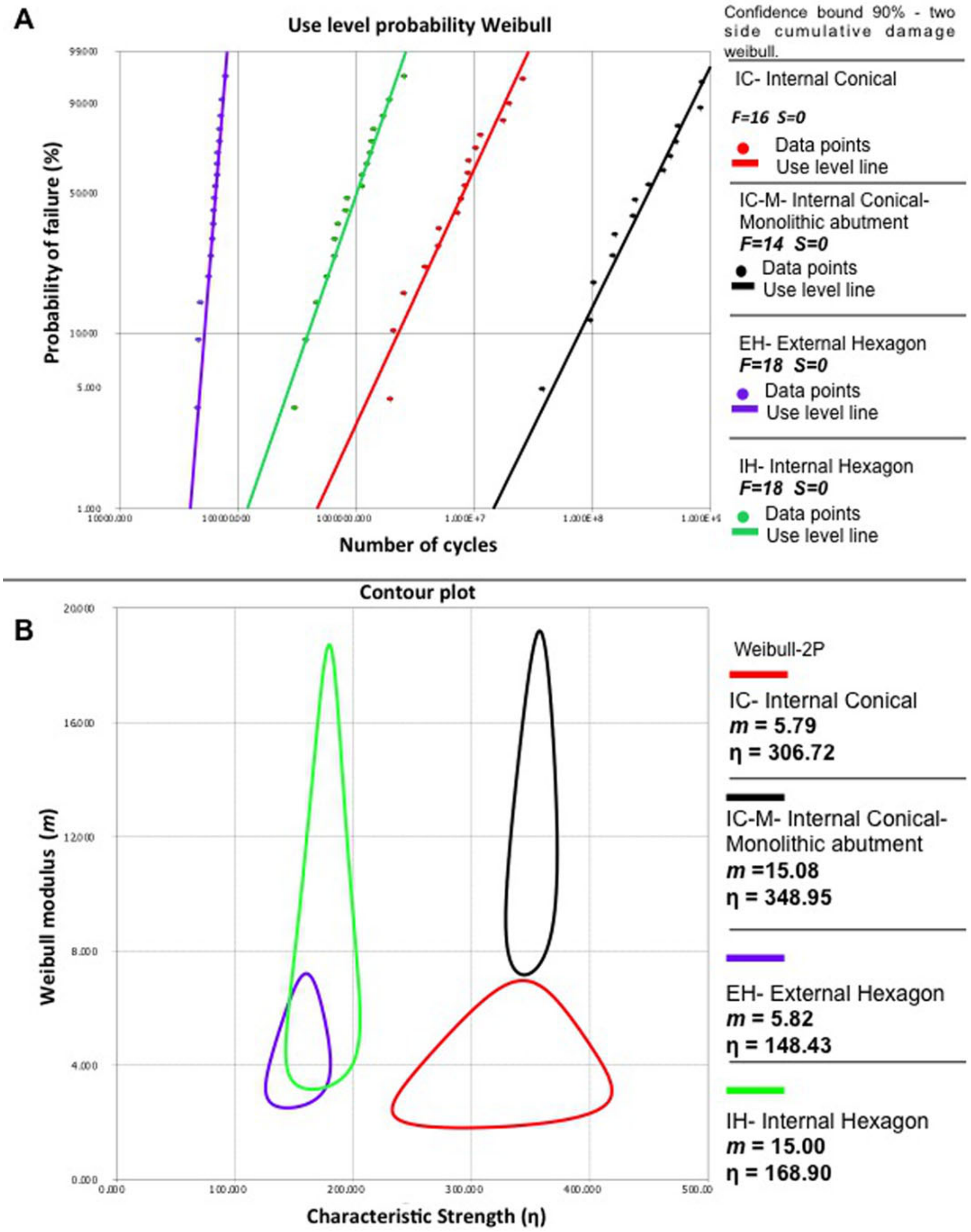

Figure 2 (A) Use level probability Weibull (90% confidence bound) showing the probability of failure vs. number of cycles for tested groups. (B) Contour plot showing "m" as an indicator of reliability (Weibull modulus) vs. characteristic strength (h), which indicates the load in which 63.2% of the specimens of each group may fail. The nonoverlap between groups indicates they are significantly different.

The profiles started at a load that was approximately 30% of the mean value obtained in the SLF test and ended at 60% of the same mean value. The SSALT was carried out on the same servo-all-electric system (TestResources 800L) under water at 9 Hz until failure (considered as fracture or bending of the screw, abutment, or implant) or until a maximum load of 500 N.[10-12]

Based upon the step-stress distribution of failures, the use of level probability Weibull curve, represented by probability of failure (%) versus number of cycles, were calculated with a 90% two-sided confidence interval (CI) using a power law relationship for damage accumulation (Synthesis 9, Alta Pro 9; Reliasoft, Tucson, AZ). The use of level probability, Weibull analysis, provides the beta (β) value, which describes the failure rate behavior over time, where a resulting $\beta < 1$ indicates that failure rate decreased over time, commonly related with early failures. $\beta \sim 1$ represents failures of a random cause, and $\beta > 1$

means that failure rate increased over time, commonly related to damage accumulation and fatigue.[18]

The reliability, which represents the probability of an item surviving a given number of cycles, was calculated with 50,000 cycles at 75 N and 200 N of load.[19,20] For the mission reliability and β parameters calculated, the two-side 90% CI was calculated as $\text{IC} = \text{E(G)} \pm Z_\alpha \text{sqrt}(\text{Var(G)})$, where IC represents the confidence bound, E(G) is the mean estimated reliability for the specified mission calculated from Weibull statistics, Z_α is the Z value from the given IC level of significance, and Var(G) is the value calculated by Fisher information matrix.[18,21,22]

The Weibull probability contour plot (Weibull modulus [m] vs. characteristic strength [η]) was constructed using final load to failure or survival of groups (90% CI). The contour plot was a graphical method that indicated the load at which 63.2% of the specimens of each group would fail. It allowed for the evaluation of statistical differences between groups based on the nonoverlap of confidence bounds.

Failure analyses

All specimens were inspected under a polarized light microscope (MZ-APO Stereomicroscope; Carl Zeiss MicroImaging, Thornwood, NY) and further scanning electron microscopy evaluation (SEM) (S-3500N; Hitachi, Tokyo, Japan) was performed for the group with the highest characteristic strength.

Results

All specimens failed after the SSALT test. The mean β values derived from the use level probability Weibull (90% two-side CI) with use stress of 100 N were 1.48, 1.40, 8.54, and 1.98 for IC, IC-M, EH, and IH, respectively, indicating that fatigue contributed to accelerating failure in all groups (Fig 2A). Significant differences between characteristic strength (η), which indicates the load in which 63.2% of the specimens of each group may fail, were indentified between groups considering the nonoverlap of the contours. EH (148.43 N, $m = 5.82$) and IH (168.90 N, $m = 15$) were not different between each other, but both presented significantly lower characteristic strength than either IC group. The presence of a monolithic abutment (IC-M) significantly increased the characteristic strength (348.95 N) and Weibull modulus (15.08) compared to the conventional two-piece abutment and screw IC group (306.72 N, $m = 5.79$) (Fig 2B).

The calculated reliability for a mission of 50,000 cycles at 75 N showed no differences between groups (Table 1). For the same number of cycles at 200 N load, the calculated reliability showed that cumulative damage reaching 200 N would lead to a decrease in probability of survival for all groups. At 200 N, no differences were observed between IC groups (based on nonoverlap between upper and lower bounds) nor between EH and IH, which were both significantly lower than either IC group (Table 1).

Failure mode in EH was consistently confined to the abutment screw ($n = 18$ fractures), whereas in IH it involved implant ($n = 18$) and abutment screw fractures ($n = 18$). In contrast, all implants were intact in the IC groups, and failures involved abutment and screw fractures ($n = 11$). In monolithic abutments, failures were restricted to abutment ($n = 8$ fractures and 6 bending). A representative image of the fractured monolithic abutment shows the most predominant fracture location (Fig 3A.1, A.2). The SEM micrograph of a representative monolithic abutment fracture after SSALT showed that the fracture initiated at the region of high stress concentration where the loading condition caused a local stress under tensile force (lingual surface), which exceeded the strength of the material (Fig 3B.1). Due to titanium's ductility, stress is redistributed creating a plastic zone (Fig 3B.2), which involves plastic deformation. A zone of rupture can be observed in the compression curl area (rupture zone) (Fig 3B.3).

Table 1 Calculated reliability for a given mission of 50,000 cycles at loads of 75 and 200 N. Different letters indicate statistical difference between groups based on the nonoverlap of upper and lower bound

50,000 cycles at 75 N

	IC	IC-TM	EH	IH
Upper bound	100%	100%	99.98%	100%
Reliability	100%[a]	100%[a]	99.26%[a]	100%[a]
Lower bound	99.9%	100%	95.67%	99.97%

50,000 cycles at 200 N

	IC	IC-M	EH	IH
Upper bound	91.13%	98.40%	11.16%	0%
Reliability	81.71%[a]	94.28%[a]	0%[b]	0%[b]
Lower bound	64.46%	80.64%	0%	0%
Beta (β)	1.48	1.40	8.54	1.98

Discussion

The first hypothesis, which suggested that implant-abutment connection design would result in different reliability, was partially accepted. At a given mission of 75 N load, all groups showed similar probability of survival, suggesting that NDI may be a reliable option to restore central or lateral incisors when taking into account mean bite forces lower than 75 N.[19] An increase in load to 200 N severely decreased the probability survival for all groups, especially for EH and IH. Failures chiefly involved the integrity of the abutment's screw in external hexagon connections, which is expected, considering that the abutment is mainly stabilized by its torqued screw eventually challenged by oblique loading.[23] In contrast, the high stress concentration at the cervical thin area of the IH connection during loading surpassed the yield strength of the NDIs, leading to the least desirable complication, implant fracture in lieu of abutments or their screws, which remained intact in this group.[24] Regarding IC and IC-M, failures were restricted to abutments and screw system; no implant fracture was observed. This result might be attributed to the friction-locking system, which protects the prosthetic components against excessive loading even in narrow diameters.[12]

Although the EH and IH standard platform implants have been successfully used for full-arch restorations, their use in

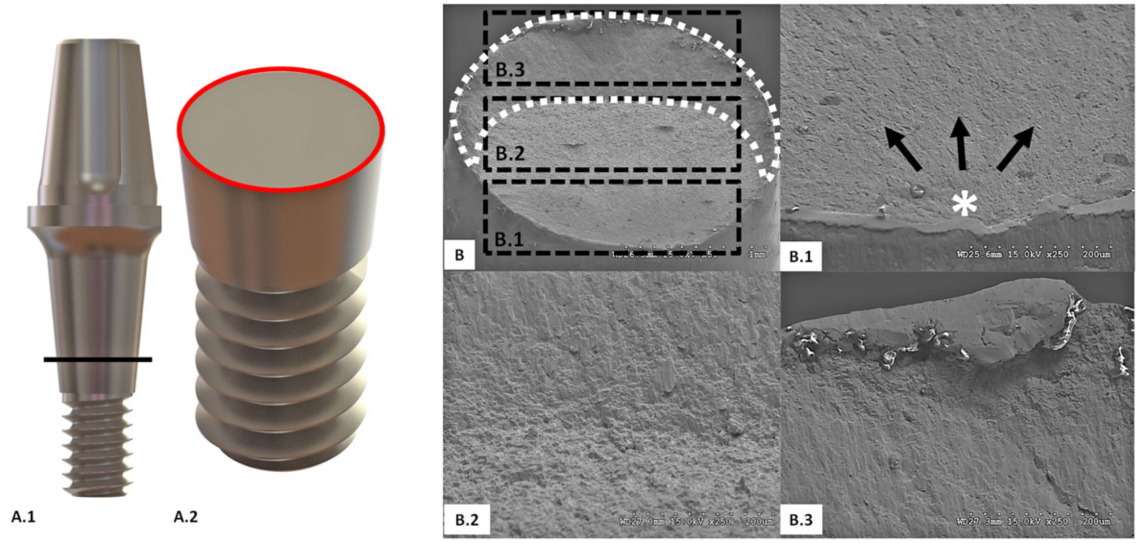

Figure 3 (A.1) Schematic image showing an overall image of the monolithic abutment. The horizontal black line represents the most predominant fracture location. (A.2) Cross-sectional area of the fractured abutment. Red line delimits the fractured area evaluated by SEM. (B) Overall image of a fractured specimen (50×). White line delimits dimple structure, typically observed in ductile materials failure. (B.1) Asterisk indicates the fracture initiation where the surface underwent tensile stress. The black arrows show the direction of stress propagation. (B.2) Transitional area (striated surface). (B.3) Rupture zone (compression stress).

load-bearing regions as single-unit crowns supported by NDIs must be carefully evaluated. The magnitude of bite force at an isolated contact of posterior teeth averages 35 N,[19] and the maximum force is in the range of 300 to 500 N.[20] In addition, the cumulative role of fatigue in strength degradation has been reported in splinted full-arch prostheses screwed on EH implants, where implant fractures increased as time elapsed, especially over 10 years.[25,26] Long-term clinical evaluations of NDIs supporting multiple-unit prostheses are warranted, given their potential benefits of avoiding bone grafting procedures while allowing patient rehabilitation at a faster pace.

The second hypothesis, which suggested that monolithic abutments would result in higher reliability, was rejected. IC-M and IC showed statistically similar probabilities of survival for both loading missions. It has been suggested that the improved stability of internal conical connections is due to their increased area between abutment and implant walls potentially decreasing micromotion between parts.[27,28] In addition, their tapered design seems to direct the stress-load toward the implants' longitudinal axis.[29] However, the CI-M showed the highest characteristic strength and the highest Weibull modulus, indicating greater structural reliability. Therefore, whereas reliability calculations were not different between internal conical groups, it is likely that predictions beyond 200 N would favor the monolithic abutment instead of the conventional abutment and screw internal conical group. A recent data compilation published on a variety of implant-abutment connection designs tested under the same parameters presented herein showed that internal conical abutments with screws consistently showed lower characteristic strength compared to monolithic abutments.[18] However, since implant macrogeometries and implant bulk materials were not standardized between groups, as done in this study, interpretation should be made with caution.

Clinically, the survival rates of NDIs are encouraging (94.7%[30] to 97.25%[31]) and comparable to standard-diameter implants. Fatigue and clinical studies are still necessary to characterize and provide guidelines to clinicians for the multitude of variables that can be incorporated in the restoration process of NDIs, such as implant bulk material, retention method (screwed vs. cemented), single versus multiple units, and many others that have been already reported for standard diameter implants.

Conclusion

The first hypothesis, that implant-abutment connection design would result in different reliability, was partially accepted. Internal conical NDIs showed the highest reliability at high loads. The second hypothesis, which postulated that monolithic abutments would result in higher reliability, was rejected. Failure modes differed between groups.

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