Effect of Dental Implant Diameter on Fatigue Performance. Part I: Mechanical Behavior

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ABSTRACT

Aim: The purpose of this study was to evaluate the effect of the implants' diameter on the mechanical function and load-fatigue performance of dental implants.

Materials and Methods: Three groups of implants with different diameters (3.3 mm, 3.75 mm and 5 mm), were tested under static and cyclic compressive loading. A total number of 15 implants for the static test and 112 implants for the cyclic-fatigue test. In the cyclic test, the machine ceased operating when the structure collapsed or when it reached 5×10^6 cycles without apparent failure. The load versus the number of cycles was plotted as curves for biomechanical analysis (S-N curve) for each implant diameter.

Results: The S-N curve plotted for the 5 mm implants showed classic fatigue behavior with a finite life region starting from 620N. The same was observed for the 3.75 mm diameter implants, with a finite life region starting below 620N. By contrast, the 3.3 mm diameter implants failed to show predictable fatigue behavior and a fatigue limit could not be defined.

Conclusions: The results of this study emphasize the importance of implant diameter on fatigue behavior. Narrow implants failed to show typical fatigue behavior which might be attributed to the implant design.

KEY WORDS: cycles, load, normalized load, probability of fracture, S-N curve

INTRODUCTION

Dental implants are widely used today as a functional and predictable solution for partial or full edentulism. Clinical research activities in implant dentistry have mainly focused on implant survival in the biological context, while the incidence of technical and/or mechanical complications that include implants and implant part fractures has only been addressed to a minor extent.[1]

A fracture implant incidence of 1.4% was reported in a retrospective study evaluating 1,500 dental implants after a follow-up time of 18 years. The study identified some of the risk factors for implant fracture as the type of the prosthesis involved (cantilever), posterior location of the implants (molars and premolars), implant diameter and the existence of occlusal parafunction (bruxism). All the risk factors described relate to the development of large loads imposed on the implant parts, which probably leads to the observed result.[2]

Simonis and colleagues,[3] in a long-term retrospective cohort study evaluating the survival and success rate of 131 dental implants after a follow-up time of 10–16 years, reported that mechanical complications incidence was 31% and the incidence of implant fracture after 10–16 years of use was 3%.

Balshi[4] evaluated the causes of implant fractures, and indicated biomechanical or physiological overload as the most common reason for implant fracture. The source of the overload is likely patient parafunction habits and incorrect prosthesis design, which might be responsible for the creation of undesired bending moments. He recommended the use of implants with larger diameters to provide larger metal bulk, therefore increasing implant strength by decreasing the applied level of stress.

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Morgan and colleagues[5] tried to reveal the nature and cause(s) of implant fractures. To this end, they compared fracture surfaces of implants that had fractured intra-orally after osseointegration to experimentally fractured Branemark implants (4 mm diameter) under overload and under fatigue conditions, using scanning electron microscopy. It was concluded that implants fractured in clinical use was caused by fatigue under physiologic loads, and that failure was aggravated by resorption of bone around the implant.

Narrow-diameter implants (Ø < 3.75 mm) are widely used today. However, the successful use of such implants was reported in a small number of clinical reports of limited number of implants, and of limited follow-up time.[6–9] Most of the studies report high survival rate of over 89% after a follow-up of up to 5 years.[6,7] However, some of these reports include incidences of implant fracture.[8,9]

In a recent review dealing with fractures of osseointegrated dental implants, it was emphasized that implant diameter has a direct influence on the occurrence of fractures because of a low resistance to fatigue, especially when placed in the posterior region.[10]

In vitro testing and characterization of the biomechanical strength performance of implant structure is seldom found in the literature. Several studies have tested dental implants using static loading, while others have used cyclic loading. Unfortunately, static therefore monotonic loading, may have very little clinical relevance as mechanical failures are more likely related to the application of repeated loads.[1] Most of the literature failed to mention fatigue as a complex failure mode, influenced altogether by the structural design, material properties and environmental effects. Most of the available publications do not include a basic plot of stress (or load) versus the number of cycles to failure, the so-called S–N curve.[11] representing the structure's (implant + screw + abutment) fatigue performance. Furthermore, most cyclic tests have focused on implant–abutment interface design, and only few studies addressed the effect of implant diameter (design considerations) on fatigue performance.

From the previously mentioned literature, it appears that while repeated loads may be considered as a potent cause for failure of dental implants, the available quantitative and systematic data is still quite scarce.

Therefore, the goal of the present study was to methodically evaluate and compare the fatigue performance of three different diameter implant structures, through the construction of S–N curves.

MATERIALS AND METHODS

Three sets of Ti6Al4V (titanium alloy) commercial dental implants were tested in this study. All the tested units consisted of 13 mm–long implants with a tapered design, and an outer diameter of 3.3 mm, 3.75 mm and 5 mm (at implant neck) connected to a straight 8 mm–implant abutment (with a standard abutment screw 7 mm long). Components were tightened to 30 Ncm with a clinical torque driver.

Mechanical testing (monotonic and cyclic) was performed using an MTS servo-hydraulic load frame (MTS System, Minneapolis, MN, USA) with 250 kN–load capacity, driven under load control. To apply loads to the tested implants and fix specimens to the testing machine, a custom-designed holding stage made of high-strength steel was machined. To fix the test implants rigidly, a specimen holder was machined, which consists of a longitudinal slotted steel cylinder. The implant was inserted into the hole of the specimen holder up to the second thread from the head of the implant. The specimen holder was then inserted to the holding stage at an angle of 30° off-axis and fixed to the testing machine (Figure 1). This way, the testing force that was applied to the implant abutment induced a bending moment, as recommended by the ISO standard for dynamic fatigue testing for dental implants.[12]

The experimental setup includes rigid clamping of the specimen to its base. This boundary condition is more severe than the more flexible condition experienced by an implant in vivo. However, the rigid

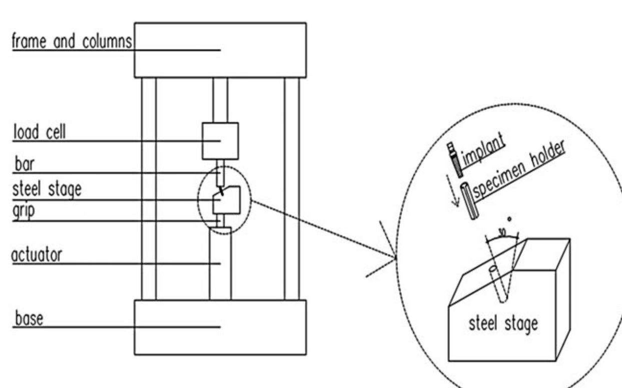

Figure 1 Schematic diagram of test set-up. To fix the specimen, a steel base was machined with a hole on its upper face so that the specimen, once inserted, would form an angle of 30°.

clamping condition used in the experiments does not affect the results and conclusions drawn in the sequel, while it allows for application of larger load levels.

To test the quasi-static bending strength of the specimens, a series of tests were performed prior to cyclic tests. Vertical load was applied at a rate of 0.4 mm/minute until the sample fractured or exhibited a significant amount of (permanent) plastic deformation (the specimen was noticeably and permanently bent) accompanied by a load drop. Five specimens were quasi-statically tested for each implant diameter, for a total number of 15 implants. The maximum applied load was recorded.

Fatigue testing was performed under load control. The instruments setup and sample fixation were the same for the static loading test. The selected load was directly applied to the implant abutment head as a sinusoidal force, with a minimum to maximum loading ratio of $R = 0.1$. The test frequencies, chosen to minimize vibrations of the test machine, were in the range of 15–20 Hz. Testing was carried out in room air at ambient temperature. The machine either stopped working when the structure collapsed, or the test was interrupted when 5×10^6 cycles were exceeded without apparent failure. After each test the number of cycles and the failure mode of the specimen were recorded. A total of 112 specimens were tested during fatigue testing. Table 1 summarizes the number of implants tested for each implant diameter.

It should be emphasized that throughout this work, testing was carried out on *structures* (implant, screw and abutment together) and not specifically on the *material* they are made of. Consequently, the fatigue results should be considered as characteristic of the mechanical design of the tested implant, and not as a typical material property.

To allow comparison, all cyclic loads were scaled to their quasi-static test strength, so that all cyclic loads for each implant diameter will be in the same normalized range of 0–1.

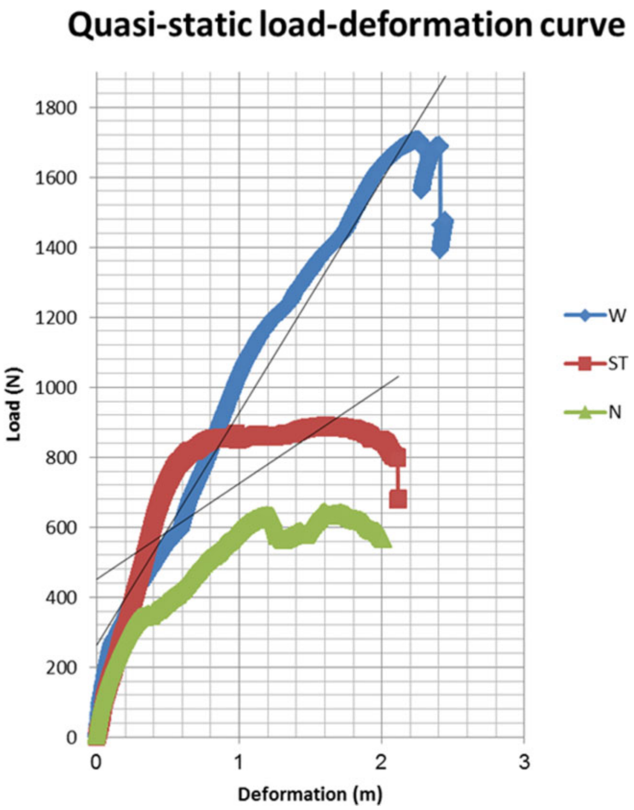

Figure 2 Typical load-displacement curve for each of the 3 tested groups. W = 5 mm implant, ST = 3.75 mm implant, N = 3.3 mm implant.

RESULTS

Static Test Results

Figure 2 describes a typical load-displacement curve for the three tested groups (5 mm, 3.75 mm and 3.3 mm implants). The highest load point for each tested implant was considered as the load to deformation. Table 2 summarizes static test result for each implant diameter.

Fatigue Test

Normalization of Fatigue Load Magnitudes. The mean load value of static tests (Table 2) was calculated for each

TABLE 1 Number of Implants Tested in Each Testing Group

No. of Specimens Tested	Implant Diameter
28	5 mm
26	3.75 mm
58	3.3 mm

TABLE 2 Static Test Results in the Various Diameter Implants Obtained in the Quasi-Static Test

Implant Diameter (mm)	*n*	Load Range to Deformation	Mean Load + SD
5.00	5	1400–1700N	1584N ± 115N
3.75	5	840–1040N	952N ± 103N
3.30	5	600–720N	674N ± 57N

TABLE 3 The Normalized Load Chosen for Each Implant Diameter Test

Fatigue Load Magnitudes (Ps)	No. Fatigue Load Levels (Ps)	Implant Diameter (mm)
0.60, 0.65, 0.70, 0.725, 0.75, 0.80, 0.85, 0.90	8	3.30
0.65, 0.75, 0.80, 0.85, 0.90	5	3.75
0.40, 0.45, 0.55, 0.65, 0.70	5	5.00

implant diameter and defined as single load-to-failure (SLF). All subsequent fatigue loads were scaled with respect to the SLF values. In order to compare each implant diameter performance in fatigue testing, the fatigue load chosen for each implant diameter was normalized by dividing the chosen load magnitude by the mean SLF, subsequently denoted by Ps. Consequently, all structures could be compared by considering the cyclic load they sustained in the range Ps = 0–1, as detailed in Table 3.

S–N Curves. Fatigue results are usually represented as a semi logarithmic plot of the applied load (in our case)/stress level versus the number of cycles (to failure) called the S–N curve. A typical S–N curve is divided into three main areas:[11]

1. Finite life region: Defined as the load range in which all the specimens fail after a finite number of cycles. Here the statistical distribution is scattered around the load (stress) (S).
2. Transition region: In this range of loads, some of the specimens fail and some reach 5×10^6 cycles without apparent failure (subsequently referred to as "run-outs", (R-O). In that range of loads, the probability of survival is calculated, and here the statistical distribution is scattered around the fixed 5×10^6 number of cycles (N).
3. Infinite life region: None of the specimens fail after reaching 5×10^6 cycles, arbitrarily considered as a limit below which fatigue failure will not occur, although this point is controversial.[13]

Figure 3, describes the S–N curves obtained for each implant diameter.

In the S–N curve obtained for the 5 mm implant (Figure 3A) the three above-mentioned S–N curve regions can be identified. The finite life region is found for Ps ≥ 0.6 (i.e., 950N). In this range, as the normalized load decreases the average number of cycles to failure increases. The transition region is found between Ps 0.4–0.6 normalized load. The probability of survival increases as the normalized load decreases. The infinite life range starts around Ps = 0.4 (i.e., 620N).

In the S–N curve obtained for the 3.75 mm implant (Figure 3B), the three distinct regions could be identified as well. The finite life region was found in Ps ≥ 0.85 normalized load (i.e., 810N). In this range, as the normalized load decreases the mean number of cycle to failure increases. The transition region is found between Ps 0.65–0.8. The probability of survival increases as the normalized load decreases. The infinite life range starts below Ps = 0.65 (i.e., 620N).

In contrast, in the S–N curve obtained for the 3.3 mm implant (Figure 3C) the three S–N curve regions could not be clearly identified. The finite life region and transition region intersect. The finite life region was found Ps ≥ 0.7 normalized load, (471N). In this range, as the normalized load decreases, the average number of cycles to failure increases. The transition region was found between Ps 0.6–0.75 normalized load. Here, the probability of survival did not increase monotonically as the normalized load decreases. The infinite life range thus could not be defined.

The overall picture for the 3.3 mm implant according to those measurements reveals an apparently inconsistent fatigue behavior, in the sense that the probability for survival did not increase as the normalized load decreases so that the infinite life limit load cannot be estimated.

In order to compare each implant diameter performance in fatigue testing, normalized load was used. Figure 4 represent a graphic description of the overall 5 mm implant and 3.75 mm fatigue performance, comparing the probability of fracture (the percentage of failed implant found in the same load magnitude) at each normalized load. The 3.3 mm implant was excluded because of its non-typical fatigue behavior.

It can be seen that the fatigue behavior of the 3.75 mm implant and 5 mm implant are similar (same slope), but the 3.75 mm implants have better performance at higher normalized load. Nevertheless, one must keep in mind that the absolute load magnitudes used in the 5 mm implants was larger than those used for the 3.75 mm implants.

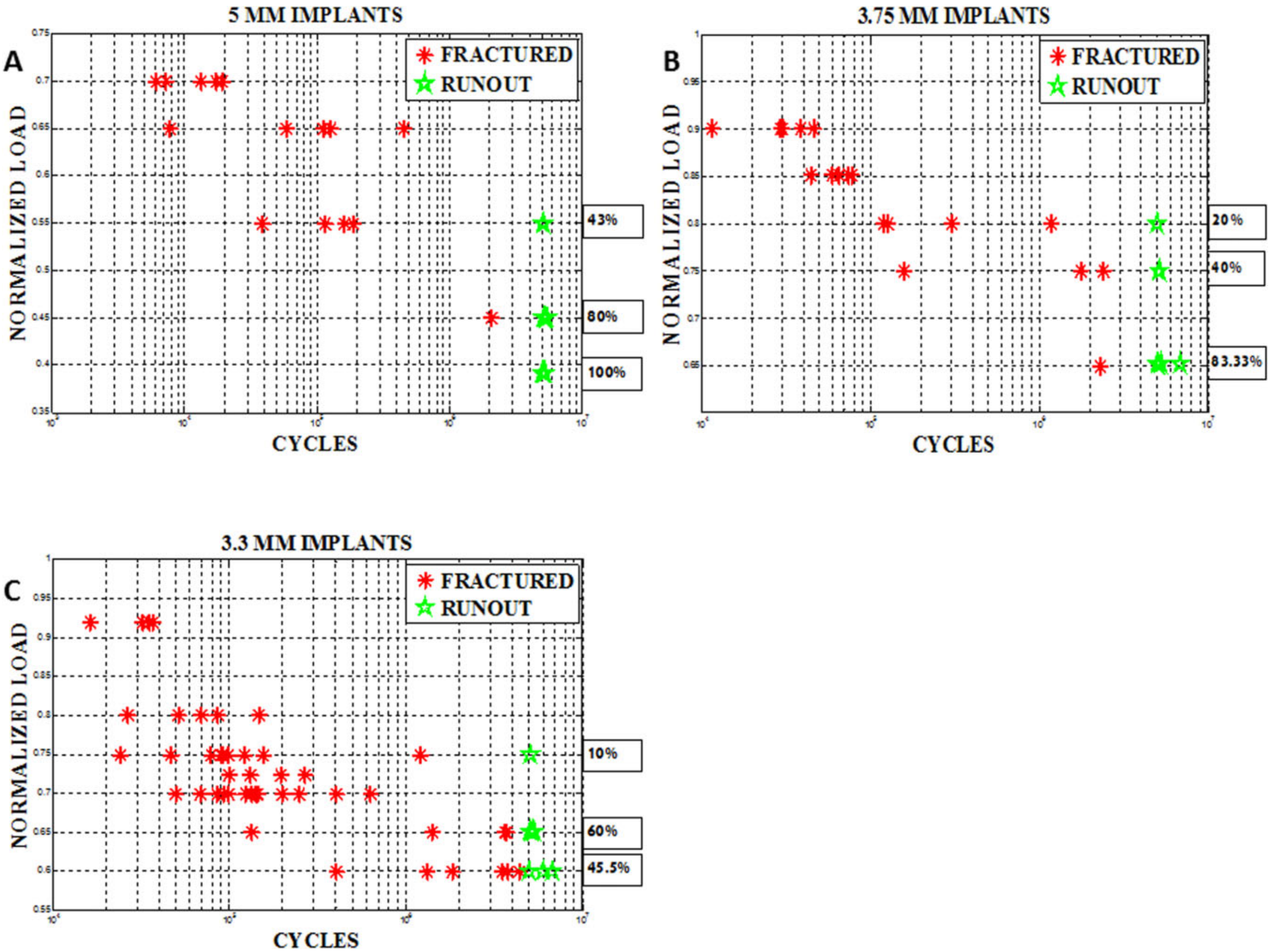

Figure 3 Load versus number of cycles in fatigue testing for 5 mm group (A), 3.75 mm group (B) and 3.3 mm group (C). Each marking on the figures indicates a tested specimen. A "Fractured" specimen (marked by the red asterisks) means that the specimen failed after a finite number of cycles. A "Run-out" specimens (marked by a green star) means that the specimen reached 5×10^6 cycles without an apparent failure. The boxes on the right of the figure describe the probability of survival at each load magnitude i.e., the percentage of implants, from the total number of specimen tested in the same load magnitude that reached 5×10^6 cycles without apparent failure.

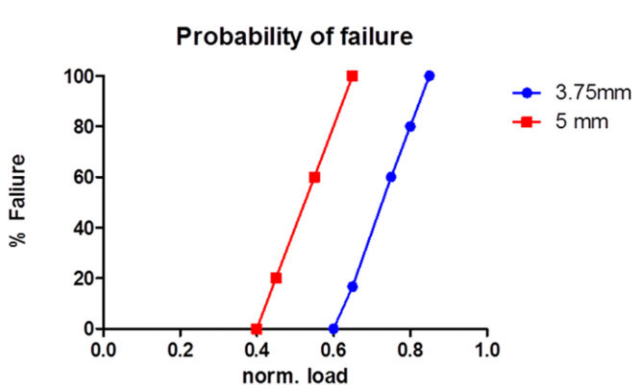

Figure 4 Probability of failure. The plot compares the fatigue behavior of the 5 mm implant and the 3.75 mm implant testing group, and describes according to the S-N results the percentage of failed implants at each normalized load.

DISCUSSION

In the present study, a significant diameter effect could be seen for the different implants on fatigue performance with 5 mm and 3.75 mm implants showing a classic comparable fatigue behavior, while the 3.3 mm implant did not exhibit a typical fatigue behavior at all.

Likewise, Quek and colleagues[14] investigated the fatigue performance of three different widths of single-tooth implants and abutments. The test results indicated implant fracture as a potential failure location in narrow 3.3 mm implants during cyclic loading, and a superior load fatigue performance of the 5 mm wide implants. This research was based on only five implants, with only one level of applied load, which is of limited nature.

Factors usually associated with fatigue behavior are related to stress concentrations generated along the structure's surface, like notches, dents, machining marking etc. The effect of such stress concentration is a clear reduction of the fatigue limit and sometimes untypical fatigue behavior.[11] The inconsistent fatigue behavior observed for the 3.3 mm implant diameter is most likely the result of such factors, which might hinder fatigue resistance and lead to the observed result. A fracture mode analysis is, therefore, required to support this assumption.

Concerning the applied loads in the present tests, one should keep in mind that the typical maximum bite force magnitude exhibited by adult is 710 N (between premolar and molar). Yet, there is a difference between men, with 789 N, and women, with 596 N on the average. An additional difference is noted between posterior teeth, which can reach up to 800 N, and anterior teeth that reach about 200 N.[15,16] Occlusal force during chewing and swallowing is estimated to be 250 N.[15]

Huang and colleagues[15] calculated that the maximum 5×10^6 testing cycles approximated 25 years of intraoral usage when referring to occlusal forces. The predictable nature of the 5 mm implant and 3.75 mm implant tested in this research, which showed that infinite life range below 620 N clearly defines them as a safe long-term dental devices as regards fatigue performance. But when referring to the maximal occlusal forces as might be the situation in bruxists with higher occlusal forces that might reach the transition range, implant fracture becomes likely, with a well-defined probability. The intraoral behavior of the narrow 3.3 mm implant tested in this work revealed unpredictable fatigue behavior.

CONCLUSIONS

Normal and wider diameter implants showed a classic and comparable fatigue behavior, while the 3.3 mm diameter implants, failed to show predictable fatigue behavior. The results of this experiment clearly show the need for a detailed fracture mode analysis in order to identify the probable causes for the observed fatigue behavior.

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