Random spectrum loading of dental implants: An alternative approach to functional performance assessment

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ABSTRACT

The mechanical (fatigue) performance of dental implants is usually assessed on the basis of cyclic tests and S/N curves. This assessment does not provide information on the anticipated service performance of the implant, nor does it allow for detailed comparisons between implants unless a thorough statistical analysis is performed, which is not required by the current certification standards.

The notion of endurance limit is deemed to be of limited applicability in the case of unavoidable stress concentrations and random load excursions, that all characterize the dental implants and their service conditions.

In this work, we propose a completely different approach, based on random spectrum loading of the implants, noting that structural lifetime assessment using this technique has long been used in aeronautical design.

Here, the implant is randomly loaded by a sequence of loads encompassing all load levels it would endure during its service life, as opposed to a series of cyclic tests at fixed load levels. The premise of this approach is to provide a quantitative and comparable estimate of its performance in terms of lifetime, based on the very fact that the implant will fracture sooner or later, instead of defining a fatigue endurance limit of limited practical application.

After assessing their static strength, 5 commercial monolithic Ti6Al4V implants were tested under cyclic, and another 5 under spectrum loading conditions at room temperature and dry air. The failure modes and fracture planes were identical for all implants, but, as expected, the spectrum loaded implants had a significantly longer service life. The results and the approach are discussed, and potential applications of the spectrum loading technique are discussed, that include systematic, straightforward and reliable comparisons of various implant designs and environments, without the need for cumbersome statistical analyses.

It is believed that spectrum loading can be considered for the generation of new standardization procedures and design applications.

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INTRODUCTION

Dental implants are widely used today as a viable and reliable alternative for tooth replacement in edentulous patients.

The success of dental implants is largely attributed to what is known as "osseointegration". This term implies an anchorage mechanism whereby artificial components can be reliably and predictably incorporated into the living bone, and this anchorage can persist under normal loading conditions (Branemark et al., 2001).

The application of this concept to dental implants has reduced the dependence on mechanical interlocking, and allowed the development of implant systems in a more versatile endosseous design. It was subsequently realized that subtle changes in shape, length, width, and surface condition of endosseous implants could influence success rates. Implant manufacturers provide nowadays a great variety of implants design, with size and shapes that have mainly evolved to fit current surgical concepts and prosthetic design (Lee, 2005).

But despite the importance of the implant's surgical and prosthetic success, dental implants are before anything else a medical device, namely a mechanical structure whose design must be optimized, with the expectation that its service life will be as long as possible, or at least *well-defined*.

As of today, the vast majority of commercial implants comply with the quality requirements defined by ISO 14801, that was developed in 2003 by a panel of industrial and academic experts for the Organization for International Standardization (ISO 14801: 2007). This standard specifies a method for fatigue testing of single-post endosseous dental implants of the transmucosal type, and it is usually invoked to obtain the certification of dental implants of different designs or sizes.

According to ISO 14801, fatigue tests should be performed on the examined structures, by cyclically loading specimens at various load levels until a lower load limit is reached (endurance limit), below which no fatigue failure is expected to occur. This load (stress) limit is set for a given number of cycles (usually a few millions). A specimen that has reached the selected number of cycles without fracturing is considered as a "run-out". The standard requires at least 2 specimens for each tested load level that "run" until failure, and 3 "runout" specimens in order to determine the endurance limit. The results are presented in a limited load-cycle diagram.

In addition, cyclic loads are applied to the dental implant body and its components under "worst-case" conditions, i.e. creating bending moments and mimicking bone loss. These test conditions are ill defined ("worst case"), and the results thus obtained cannot be applied to predict the in-vivo performance or longevity of the dental implant or prosthesis.

A number of different fatigue testing procedures dealing with the estimation of a structure fatigue life are commonly used today. The most common and well-studied procedure is the "total-fatigue life approach" (Suresh, 1994). Fatigue testing is carried out as the evaluation of the number of cycles that the specimen can withstand until fracture. The tested material/ structure is subjected to a constant amplitude of cyclic stress or strain. The results are summarized in what is called an S/N (stress vs. cycles), or Wöhler curve. Fatigue testing at constant load amplitude provides valuable insights into the mechanistic processes, i.e. fatigue crack initiation and propagation (Suresh, 1994). The interpretation of the results requests a careful consideration of their statistical nature, a point that has long been noticed in the engineering community. In fact, it is routinely observed that identical specimens that are subjected to the same periodic loading amplitude, will exhibit vastly different performance in terms of cycles. Consequently, one should usually test a relatively large number of specimens per stress level in order to obtain meaningful statistics and estimates of the fatigue performance of a material, with a specified level of confidence (Milella, 2013). Such tests are naturally time-consuming, and relatively few investigations care to dwell on the statistical nature of fatigue, by simply cutting down the number of tests, in both the load levels and number of specimens. In that respect, the ISO 14801 recommendation clearly overlooks the statistical issue of fatigue. A central outcome of the S/N curve is the so-called "fatigue or endurance limit, namely the cyclic stress magnitude below which the specimen can be cycled indefinitely without failure (Suresh, 1994). This concept has been quite well established for decades, and it was found to apply to most materials. However the very notion of an "endurance limit" has been questioned by Batias et al. (1999) who investigated fatigue in the gigacycle regime. According to those authors, the observed lack of failure after a few million cycles can in no way be extrapolated to longer times.

Since the fatigue limit is considered as one of the prime goals of fatigue testing, accelerated procedures have been developed over the years that allow for its quick determination, such as the staircase method which is routinely applied and improved (Morrissey and Nicholas 2006; Milella, 2013; Hirata et al., 2014) , or questioned (Wallin, 2011).

At this stage, one should differentiate between material and structural fatigue testing. Material testing simply implies that a material and its thermomechanical condition and/or environment are evaluated in terms of fatigue performance. The results of the evaluation provide guidelines to the structural designer as to *material selection*.

By contrast, *structural fatigue testing* means the evaluation of a given structure under repeated loading, in which the material itself is only one of the key factors, when other design issues such as stress concentrations must be taken into account. Therefore, structural testing considers first and foremost the structural performance of the tested component. As of today, those fundamental issues are largely overlooked in the fatigue certification process of dental implants, as there is no specific requirement for a thorough failure analysis and failure loci identification, so that the designers can make use of safety factors to lower the local stresses levels (Budynas and Nisbett, 2010). In other words, the fatigue *performance* of dental implants is not clearly identified, if one relies solely on the ISO standard recommendations for instance. Yet, this information is crucial for both the manufacturer and end-user of the dental implants, as it is for any other mechanical structure.

An alternative to the traditional total fatigue life approach and S/N curves can be to test the *functionality* of the dental implant, in the spirit of Palmgren-Miners's cumulative damage approach (Milella, 2013). The latter writes as:

$$\sum_i \frac{N_i}{N_{fi}} = 1$$

where N_i and N_{fi} stand for the number of cycles at constant load level *i*, and the number of cycles to failure in the same cycle, respectively. When the cumulative value of this damage parameter reaches 1, the structure is deemed to fail. Therefore, provided a detailed S/N curve is available, one can in principle predict the longevity of a structure for any kind of loading sequence, based on this approach. However, it must be kept in mind that the cumulative damage concept has severe limitations, as it overlooks the effect of overload peaks, or assumes that loads that are inferior to the fatigue limit have no contribution to damage, as discussed, e.g. in Schijve (2003).

Spectrum loading has long been implemented in the aeronautics and space industry, or in earthquake engineering as part of the final validation process of the structural design stage.. Such a spectrum can be aimed at mimicking the various loads experienced by the component during a typical flight or earthquake for instance (Milella, 2013). In that case, the test does essentially evaluate the component as a whole, and its ability to withstand successfully such a spectrum (functionality), for which both the frequency and the amplitude of the loads can vary either randomly, or according to a pre-recorded sequence (Schijve, 2003). In the aeronautics industry, the spectrum consists of a typical flight recording of the stresses experienced by a full-scale component of interest, that is then continuously "played" in the laboratory on similar components under development. Load spectra are well documented and can be found as part of the design recommendations of the FAA (AC 23-13A) for example. In the biomedical field, spectrum loading that mimics a typical daily routine, consisting of walking and stair climbing steps, has also been applied to the testing of hip-joint replacement prostheses (Styles et al. 1998).

However, to the best of the authors' knowledge, such an approach has not been considered yet in the field of dental implant technology, and the goal of this paper is to introduce our procedure for random spectrum loading of dental implants.

In doing so, the characteristic features of human mastication should be carefully taken into account, as they are of prime importance to devise a realistic load spectrum and assess the outcome of the tests.

Prostheses supported by dental implants, are subjected to various forces, and moments. The force applied to an implant is extremely variable, and its magnitude depends on the patients' characteristics (age, gender, oral habits, etc.), type of prosthesis (single crown, overdenture, full partial denture (FPD), cantilever etc.), number and position of the implants, as well as type of food consumed, such as carrots, meat etc. (see e.g., Brunski, 2000 ; Misch, 2008).

These loads have been measured and found to be similar to those experienced by natural teeth (Misch, 2008). It has been reported that from human patients, the axial components of the *bite* forces can range anywhere from 100 up to 2400N (Brunski, 2000), and the transverse forces are around 30N (Richter et al., 1998).

It has also been established that the actual time during which chewing forces are applied on a tooth/implant is of the order of 9 minutes each day. Forces are also applied during swallowing that occurs about 480 times a day. Therefore the total loading duration for teeth / implants is about 30 minutes daily (Brunski, 2000; Misch, 2008). Finally, concerning the frequency at which the loading is applied, a range of 48-112 cycles/minute was reported by Buschang et al. (1997).

In conclusion, the loads transferred to implants and their components are extremely variable and random in nature, as they can vary in both their magnitude and duration. From this literature survey, it appears that, contrary to the other above-mentioned domains, devising a realistic mastication spectrum that would be deemed representative is quite difficult due to the wide variation in the service parameters. Yet, one can conceive two types of bounds, namely the range of mastication frequencies and that of the applied loads, as discussed in the sequel.

The aim of the paper is to introduce a new concept of fatigue testing of dental implants and their components, which considers *functionality fatigue testing* with random spectrum loading, as a more "natural" alternative to cyclic loading, aimed at mimicking the mastication dynamics (to some extent).

Consequently, the paper is organized as follows. We first introduce the materials and methods, with emphasis on the nature of the random spectrum and the tests carried out. Next we report results of such random fatigue tests along with selected fatigue tests results for which the loading was periodical, to allow for some comparison between the methods. The work includes a detailed failure analysis examining the fracture location on the implant specimens and a fractographic failure analysis using a scanning electron microscopy (SEM).

The method and the results are then discussed with respect to more conventional fatigue tests, followed by a concluding section.

MATERIALS and METHODS

About the implants

The investigated dental implants are commercial Ti6Al4V, 3.6 mm diameter, 11.5 mm length monolithic implants, manufactured by Sigdent (Israel). Those implants were selected without consideration of the implant's geometry, surface condition or other related factors. The implants were solely selected to establish the proof of concept of the spectrum loading approach, excluding any other specific mechanical consideration such as their performance. With that, the fact that they are monolithic reduces the multiplicity of potential failure sites in the different components of the implant. A representative implant is shown in Figure 1. As mentioned, the implant is monolithic and consists of two main parts, the abutment and the threaded part.
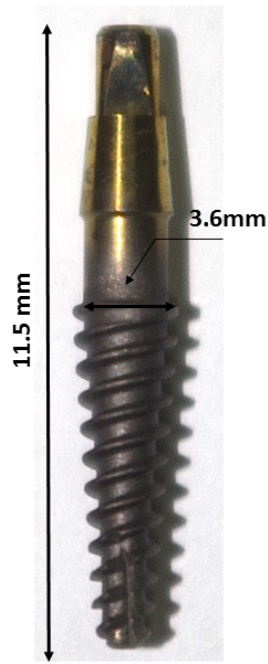

Figure 1: Tested implant

Test setup

All mechanical tests were carried out using an Instron (model 1342) servo-hydraulic machine, operated under compression load control.. A programmable controller (Shimadzu 4830) was used to drive the loading apparatus. The Instron machine was equipped with a load- cell of 3000 N full capacity. All the tests were carried out in room air at ambient temperature.

In order to fit the implants to the testing machine, each implant was inserted into a specially devised cylindrical sleeve in which a cavity reproducing the screw dimensions was machined using CNC milling. Such a setup and machining procedure ensured a high level of reproducibility along with

excellent implant gripping. Each implant was inserted in its sleeve such as to leave only the unconstrained abutment (Figure 2a). All the sleeved implants were inserted and fixed into a massive steel block, allowing for implant tilt of 30° with respect to the machine loading vertical axis (Figure 2b).
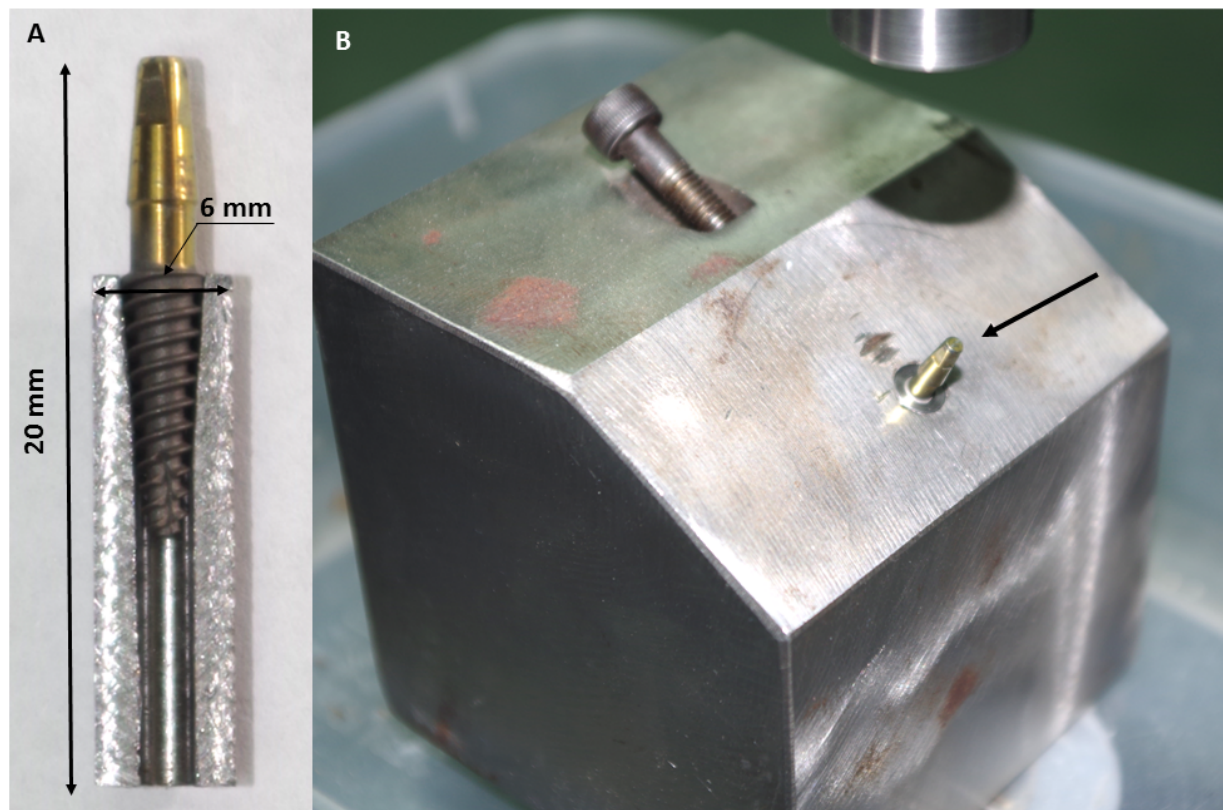

Figure 2: (a) Sleeve-implant, (b) Test setup

The rationale for such a test configuration comes from the fact that all fractured implants that were analyzed so far clearly revealed the operation of bending loads induced fatigue (Shemtov-Yona and Rittel, 2014). To this one should add the fact that mastication loads are not comprised of a pure axial biting component. It is therefore necessary to apply the load at a given angle to induce a bending moment. We chose an angle of 30°, a commonly accepted value (ISO 14801:2007).

Mechanical tests

Three kinds of tests were performed. The first, quasi-static, consisted of loading (displacement control) the implants until fracture or significant permanent bending, accompanied by a noticeable load drop. The maximum load was recorded as the "failure load", indicative of the maximum

sustainable load for the tested implants. This load was used in order to set a limit on the subsequent cyclic tests. A total of 4 specimens were tested quasi-statically.

The second, cyclic fatigue loading was carried out in the range of 0-1000 N (R=0), at a 4Hz frequency, on a total of 5 specimens. As will be reported and discussed in the sequel, a maximum load of 1000N is quite close to the average failure load of the tested implants. The outcome of the test was the number of cycles to failure, which was then converted into the total time to fracture.

The third kind of tests, spectrum loading, was designed as follows. The signal was comprised of a succession of sinusoidal blocks, each of which consists of a repetition of negative (compression) half-cycles. Each block is randomly assigned a number of 10-100 such cycles. The frequency of the block was randomly assigned to vary between 1-4 Hz. The maximum duration of the random block was determined by the frequency of the specific block and the number of cycles it contains. The amplitude of the signal was randomly assigned to vary between 0 and 1. The value of 1 represents the maximum load that may be applied to the implant. A maximum representative load was selected to be 1000 N, identical to the load applied in the cyclic tests. Pauses are randomly applied during the spectrum, with a probability of occurrence of 0.1. In that case, the block is randomly assigned a 0 amplitude, and its duration determines the duration of the pause.

A total of 5 implants were tested, all of which underwent identical spectrum loading.

The outcome of the test was the total time to fracture, expressed in seconds, including the pauses. This parameter cannot be directly converted into cycles due to the random nature of the applied loads. A typical random spectrum is shown in Figure 3a as a time series. Figure 3b is a histogram showing the load value distribution for this specimen, in increments of 100 N.
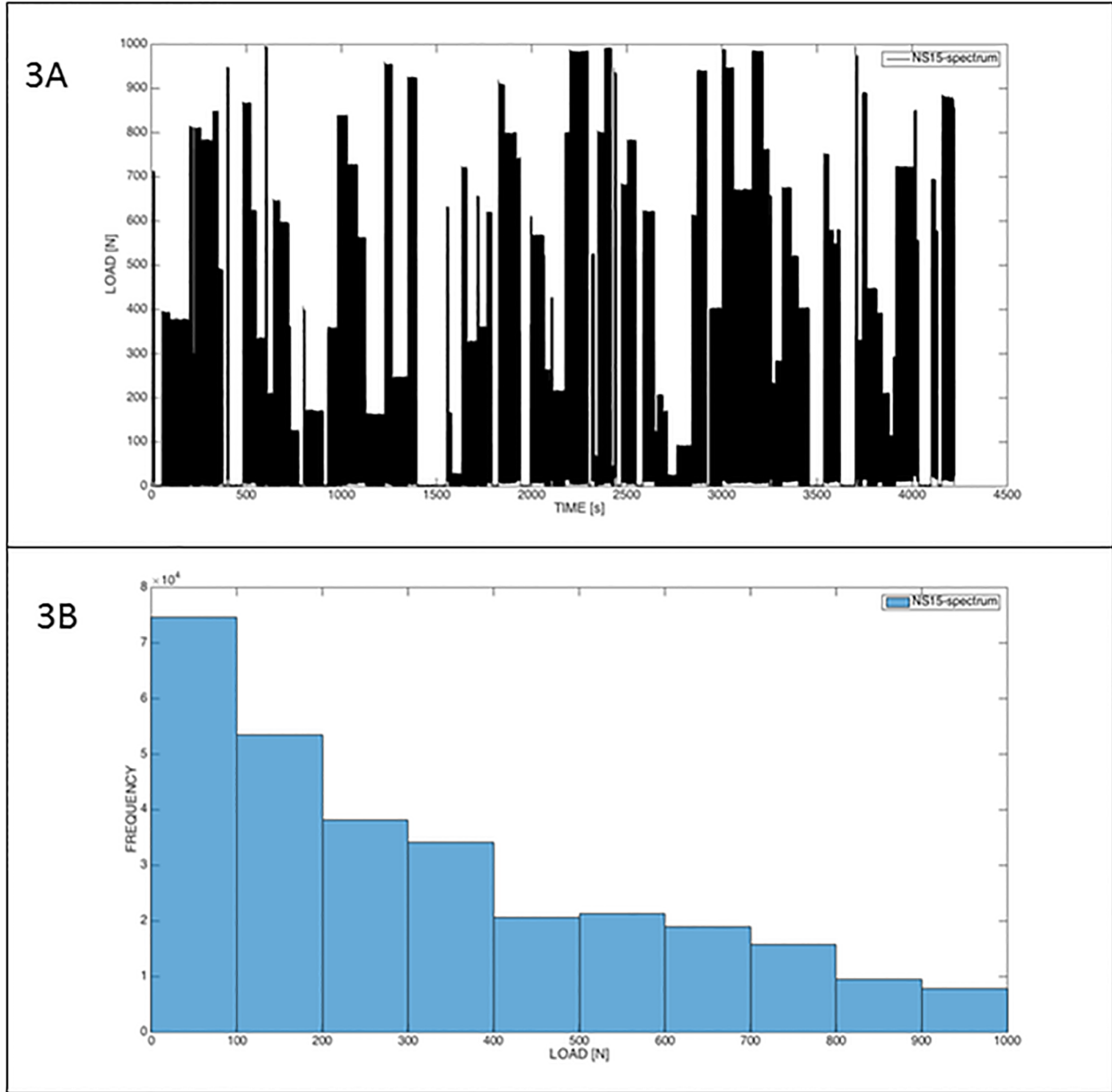
Figure 3: Random spectrum. A. Typical random spectrum B. Histogram showing the load value distribution of a representative random spectrum specimen

Failure analysis

Finally, the location of the fracture plane was recorded for each broken specimen in each tested group. A fractographic failure analysis of selected fracture surfaces from group was performed using a scanning electron microscope (SEM).

RESULTS

Mechanical tests

Table 1 summarizes the results of the quasi-static tests. The failure load is found to be $\overline{F}_{max} = 1136.5 \pm 57.1\,N$.

SPECIMEN	MAX. LOAD [N]
1	1137
2	1189
3	1163
4	1057
AVERAGE	**1136.5**
STD. DEVIATION	**57.1**

Table 1: Quasi-static test results

Table 2 summarizes the results for the cyclic test, and Table 3 for the random spectrum tests. For the cyclic tests, the average number of elapsed cycles was found to be $\overline{N} = 507 \pm 207.1$ The average time to fracture was found to be $\overline{t} = 101 \pm 41.4\,s$ For the spectrum tests, the average fracture time was $\overline{t} = 4644.4 \pm 3042.3\,s$.

CYCLIC TEST specimen	FRACTURE TIME [s]	CYCLES	POINTS>20N	POINTS>980N	N980/N20 [%]
1	151	753	17820	1780	9.99
2	101	506	10510	895	8.52
3	71	354	7416	545	7.35
4	133	664	13558	865	6.38
5	51	256	5551	471	8.48
AVERAGE	**101.0**	**506.6**	**10971**	**911**	**8.10**
STD. DEVIATION	**41.4**	**207.1**	**4895**	**521**	**1.40**

Table 2: Cyclic test results

SPECTRUM TEST specimen	FRACTURE TIME [s]	POINTS>20N	POINTS>980N	N980/N20 [%]

1	3709	252838	1777	0.70
2	2439	171783	1574	0.91
3	9944	653354	2394	0.36
4	4224	286988	1610	0.56
5	2906	231176	1829	0.79
AVERAGE	**4644.4**	**319228**	**1837**	**0.66**
STD. DEVIATION	**3042.3**	**191429**	**330**	**0.21**

Table 3: Random spectrum test results

In order to gain a refined insight into the load distribution, the following point counting procedure was used. A threshold load level of 20 N was selected as corresponding to "background noise" below which load points should not be counted. The number of recorded points greater than 20 N can be considered as the total number of recorded load points. Likewise, the number of points exceeding 980 N can be considered as representative of the high end (close to maximum load) of load levels. The ratio of the high to total load points is listed in Table 2 for the cyclic, and in Table 3 for the random spectrum tests. One can note that this ratio is one order of magnitude greater for the cyclic tests, when compared with the random ones.

Failure analysis

Considering now the fracture process, it is interesting to note that both the cyclically and the spectrum-loaded specimens all failed by fracture located in the second thread (Figure 4). This similarity illustrates the fact that, despite the different nature of the dynamic tests, the failure mechanism (fatigue) develops at the same location.

Figure 4: Fracture in the second thread of cyclic and spectrum loaded specimens.

Typical fracture surfaces of a cyclic (a) and a spectrum-loaded implant (b) are shown in Figure 5. The fracture surfaces are comprised of the fatigue and the overload regions. In both cases, the fatigue cracks are relatively short with respect to the implant diameter. This is reflected in the relatively short fatigue life of the tested implants.

Secondary cracking, perpendicular to the main fracture plane can be identified at higher magnification, which are the dominant indication of fatigue crack growth process in titanium alloy (Shemtov-Yona and Rittel, 2014). At higher magnifications, striations can be observed on both tested groups.

While the cyclic tests can be considered as low cycle fatigue, the spectrum tests correspond to a random mixture of high and low cycle fatigue. The fractographic examination did not reveal major differences in the fracture mechanisms of random vs, cyclically loaded specimens. They all comprised striations and secondary cracks. Due to the random nature of the spectrum loads, the interstriation spacing is expected to vary significantly at the local scale, while for the cyclic tests, it should grow monotonically. Here, the focus was on the main features of the fatigue failure

mechanism, as reported. All in all, whether cyclically or spectrum loaded, the failure micromechanisms of the tested implants are identical, as expected.
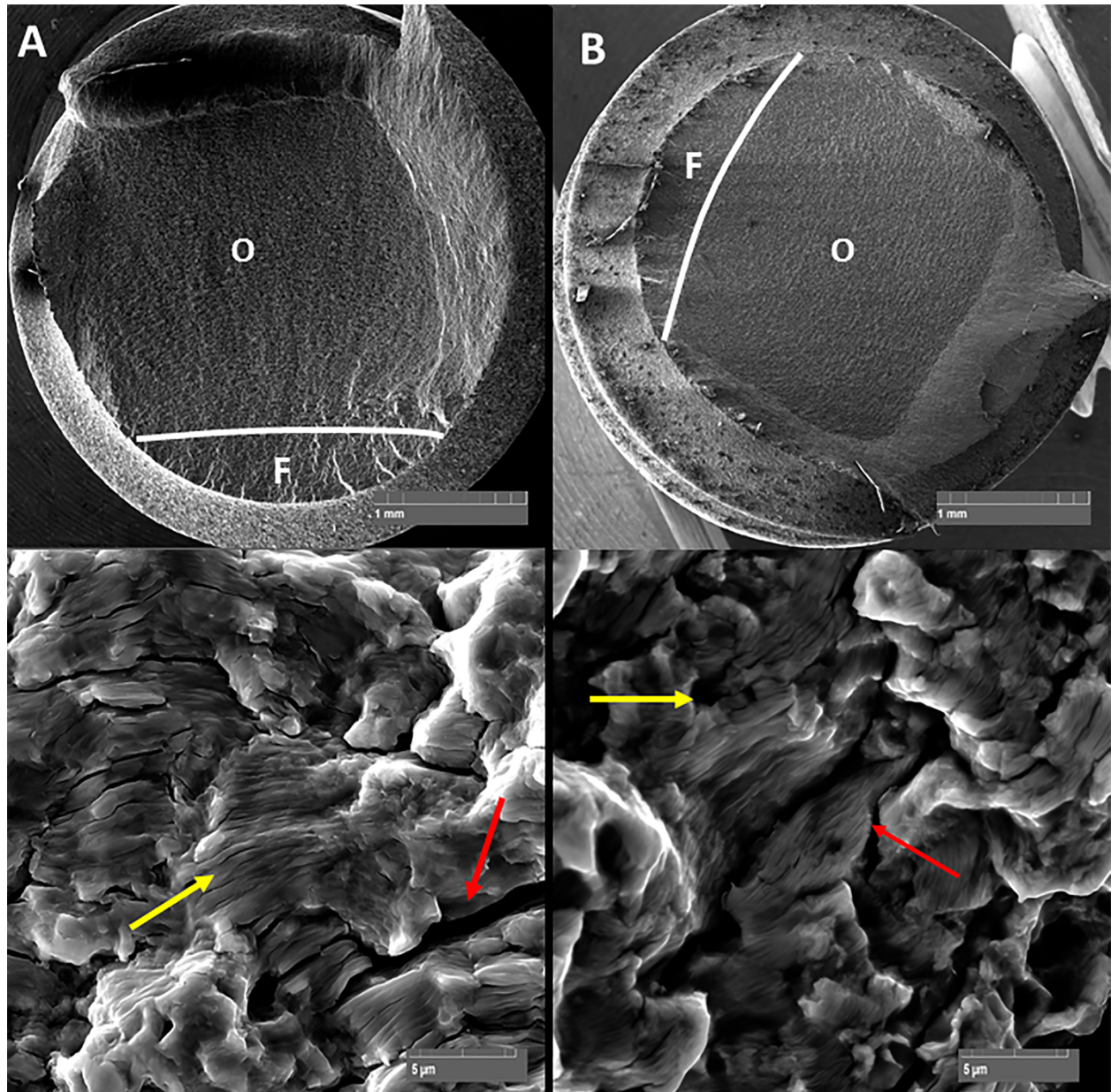

Figure 5. Typical fracture surfaces of (a) cyclically loaded, and (b) spectrum loaded implants. In low (upper panel) and High (Lower panel) magnification. The "Fatigue" (F) and "Overload" (O) areas are marked. The red arrows in the lower panels indicate secondary cracking and the yellow arrows indicate fatigue striations

DISCUSSION

We have presented a different approach for the assessment of the mechanical durability and fatigue performance of dental implants. This procedure aims at mimicking the nature of oral mastication loads by applying randomly selected loads that vary both in their magnitude and frequency. The main outcomes of this work will now be discussed in the coming paragraphs.

Real life service conditions of a dental implant are quite complex, and we chose to focus at this stage on the loading issues and devised a random spectrum loading testing system that comprises the span of loads levels that are characteristic of oral mastication. Here, one should note that the upper bound of the applied load couldn't exceed the static strength of the implant, even if the latter (1136.5 [N]) is markedly inferior in the present study to the maximum reported value of mastication loads (2400 [N]). In all cases, the static strength is considered as an upper bound, set in the present study to 1000 [N]. Note that while such information is of prime importance, it does not appear as a recommendation for the clinical use of the implants. Here it must be noted that implants are used by all patients, usually with no prior considerations of the loads exerted during their day to day mastication habits, including patients with parafunction habits in which implants are not considered a clear contraindication (Manfredini et al., 2014).

In order to replicate the actual service conditions in laboratory tests, one must consider the constantly varying environment and varying temperatures conditions. In addition, selecting a spectrum that faithfully simulates actual life mastication in terms of frequencies will necessarily be time consuming, tending to last for the several years of anticipated service of the implant. This cannot be realistically mimicked, but the whole process can certainly be accelerated by taking advantage of the fact that for metals, the actual frequency of the applied loads is of minimal importance, as hysteretic heating is negligible, as opposed e.g. to polymers (Rittel and Rabin, 2000).

The loading spectrum contains periods during which the implant is almost not loaded (pauses). Those pauses correspond in a sense to actual pauses experienced by the implant in-vivo. While at this stage, the deliberately introduced pauses do not affect the fatigue response in room air, they

nevertheless may become significant when a different environment is tested, that involves corrosion under its various forms.

From simple considerations of cumulative damage (e.g. Palmgren-Miner), it appears that whenever high loads are applied, they shorten the fatigue life of the implant. Yet, the great advantage of the spectrum loading procedure is that it encompasses *all possibly applied loads in a random sequence, and not just a fixed cyclic range of values*, as every load step contributes to the failure. As such, spectrum loading is much more attractive and realistic than cyclic loading.

It can be argued that the actual lifetime of random loaded implants, which was obtained it these tests, is relatively short with respect to actual service lifetimes. While we used a one and same spectrum to evaluate all the implants, this spectrum is not an exact duplication of the actual service conditions. The experiments aim at simulating actual mastication load magnitudes, but their frequencies and pause times are neither those encountered in real life, nor is the selected 30° angle for the application of the load. This does not detract from the validity of the results since *the same spectrum was applied to all the tested implants*. In other words, if a group of implants possesses a longer life than another group for this specific (or any other) spectrum, it can reasonably be surmised that this group will most likely perform better (longer) under real life conditions. In that respect, the proposed method can be considered as a comparative tool to rank the functional performance of various kinds of dental implants.

The reported results call naturally for a comparison with standard fatigue testing, to the extent such a comparison is meaningful. So, one should first note that in both cyclic and random tests, the fixed R ratio (minimum to maximum load ratio) is similar, and close to 0, as would be encountered in real life. This parameter too, can easily be made to vary randomly. Other than that, no further comparison between cyclic and spectrum loading results is possible in a more quantitative way. Cyclic and spectrum testing are widely different tests with a single possible relation, namely cumulative damage considerations.

The determination of an accurate S/N curve necessitates a serious statistical treatment as mentioned earlier. This means that, in order to have a high degree of confidence, the number of tested specimens per load level can be relatively large, and that once in the transition regime where implants start to 'runout", special care must be exerted to determine the probability of survival at each load level. Furthermore, the identification of the fatigue limit is not straightforward and

requires a large number of tests, unless accelerated testing procedures are applied. Plainly translated, this means that the large number of required specimens to obtain a meaningful S/N curve can be quite costly in terms of time and cost. By contrast, one could devise in principle a "standard spectrum", in the spirit of the spectra used in aeronautical design (e.g.Van Dijk and de Jonge 1975; Mitchenko et al. 1992), by which implants would be assessed to evaluate and compare their long term service performance.

Such standardization, as it exists in other domains (e.g. aeronautics), already provides all possible situations within this prescribed range, and by that it lifts any uncertainty related to load selection in standard S/N tests, thereby circumventing the fatigue limit concept. Stated otherwise, the premise of this work is that, instead of looking for a fatigue limit at which the applied load levels are low, and comparing the hypothetical averaged mastication load to it, one assumes that the dental implant will fail sooner or later, as any other mechanical structure, and consequently aims to extend its time to fracture as much as possible.

The results will of course vary statistically and a certain number of specimens should still be tested, to get a representative span of lifetimes. Yet, the spectrum approach will necessitate far less specimens and time than that required for a full S/N curve determination, which is an obvious advantage.

The proposed procedure will not only yield much more realistic results, but also provide an efficient tool to compare implant designs, materials, surface treatment procedures, environments, all rapidly and reliably. Specifically, the same spectrum can be used to evaluate to different kinds of implants, keeping in mind that they will experience similar in-vivo loads, embodied in the test spectrum. Likewise, the proposed approach can yield rapidly valuable information on the assessment of a modified vs. standard implant design. Last but not least, specific situations can now be probed, again rapidly and reliably. Those include surface condition treatments and their influence on the mechanical reliability, or simply testing in different saliva-mimicking media. In other words, the proposed approach is a basic platform for the estimation of the mechanical performance of dental implants that can be applied to many different situations and configurations. It is therefore suggested that the present approach be considered as a future addition to the existing standard(s) for dental implants certification, in the spirit of the reference spectra used in aeronautical design.

To summarize the discussion, the new approach to the assessment of the fatigue performance can now be carried as follows.

- Evaluation of the static strength of the implant.
- Selection of the peak applied load during spectrum testing, if desired. Note that such a limit is not mandatory if one wants to consider a pre-determined range of eventual service loads irrespective of the implant strength.
- Perform 5 (or more) spectrum-loading tests to estimate the longevity of the implant group and its variability.
- If necessary, repeat the procedure for each group of tested implants.
- Perform a statistical analysis of the results (e.g. analysis of variance) to rank the groups.

CONCLUSIONS

The fatigue performance of dental implants can be reliably assessed using spectrum loading.

Spectrum loading of dental implants saves time, and provides results that are more realistic than S/N curves, while being directly exploitable.

Spectrum loading of dental implants is a basic platform to compare rapidly their performance under design, atmosphere, surface conditions and other changes that are all characteristic of dental implants.

A representative spectrum could be agreed upon, as in aeronautical design, and certified to serve as the basis for future standard testing and development of dental implants.

Acknowledgement

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Figure captions

Figure 1: Tested implant

Figure 2: (a) Sleeve-implant, (b) Test setup

Figure 3: Random spectrum. A. Typical random spectrum B. Histogram showing the load value distribution of a representative random spectrum specimen

Figure 4: Fracture in the second thread of cyclic and spectrum loaded specimens.

Figure 5. Typical fracture surfaces of (a) cyclically loaded, and (b) spectrum loaded implants. In low (upper panel) and High (Lower panel) magnification. The "Fatigue" (F) and "Overload" (O) areas are marked.   The red arrows in the lower panels indicate secondary cracking and the yellow arrows indicate fatigue striations