On the mechanical integrity of retrieved dental implants

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Highlights

- 100 biologically failed implants were examined for signs of mechanical defects.
- 62% of the implants contained crack-like defects and full cracks.
- More CP-Ti implants contained defects than the Ti-6Al-4V ones.
- Implant width and length did not correlate with the observed damage.
- Surface roughening by grit blasting was correlated with defects.
- Embedded particles are linked to the generation of surface defects evolving into full cracks.
- Implants' fracture incidence will increase with reduced rate of biological complications.

Abstract

The objective of this work is to investigate the potential state of mechanical damage in used, albeit mechanically intact, dental implants, after their retrieval from the oral cavity because of progressive bone loss (peri-implantitis).

100 retrieved dental implants were characterized with no medical record made available prior to the analysis. The implants' composition, dimensions, and surface treatments were characterized using Energy Dispersive X-Ray Analysis and Scanning Electron Microscopy (SEM-EDX). Each implant was thoroughly examined for signs of mechanical defects and damage.

The implants represent a random combination of two materials, Titanium alloy (Ti-6Al-4V) and commercially pure Titanium (CP-Ti), surface treatments and geometries. Two kinds of surface defects were identified: crack-like defects and full cracks that were arbitrarily divided according to their length and appearance. We found that over 60% of the implants contained both crack-like defects and full cracks. In the retrieved sample, we observed that the CP-Ti implants contained more defects and cracks than the Ti-6Al-4V ones. For the various surface roughening treatments, a general correlation with the presence of defects was observed, but without a clear differentiation between the treatments. The high incidence of embedded particles among the observed defect further strengthens the role played by the particles upon defects generation, some of which later evolve into full cracks. It was also found that the dimensions of the implant (width and length) were not correlated with the observed defects, for this specific sample.

Our observations indicate that early retrieval of biologically failed implants, many of which contain early signs of mechanical failure as shown here, does actually hinder the later occurrence of implant fracture. It seems that once biological complications will be successfully overcome, such defects might grow later into full cracks as a result of cyclic mastication loads (fatigue). In such a case, the occurrence of implants' fracture is likely to markedly increase.

Introduction

Treating partially dentate patients with dental implants is generally considered today as a safe and predictable treatment, with a ten-year survival rate of over 93%[1]. That means that after a follow up time of 10 years, 93% of the implants are still in the jaw bone and 7% had to be removed and are considered lost.

During service, implants, just like any other mechanical structure, may experience complications. Those complications can be of a biological or a mechanical nature. Complications, as severe as they can be, do not necessarily lead to the loss or extraction of the implant and more often they can be treated and/or controlled.

Unfortunately, some can lead to the implant loss. Implant loss can be divided into two categories. The first, early losses, which occur no later than 6 months after implantation, or before the implants are loaded. The second, late losses, occurs beyond a period of 6 month after implantation.[1-4]

Early losses are mainly of a *biological* nature, during which the process of osseointegration could not be achieved due to surgical trauma, infection during the implant placement and the healing process, and instability of the implant due to premature loading. More than 50% of implant losses are defined as early losses.[3-5]

Late losses can be divided into two groups, according to the cause of loss. Biological causes are related to progressive loss of bone support around the implant because of infection or inflammation, termed peri-implantitis.[1-4] Approximately 50% of implant losses are defined as late losses, which occur due to loss of bone support. [3-5] Most of these losses occur during the first year after loading.[4]

Snauwaert et al.[6] studied implant lose rate, with emphasis on occurrence over time, of 5000 implants after a follow up time of 15 years. 60% of late biological losses occurred 1 year after loading, and 40% occurred from the second year on.

The second cause for implant loss is related to *mechanical complications*. Mechanical complications are a generic term for mechanical damage of the implant, its components, or to the suprastructure supported by the implant. Implant loss, in the context of mechanical complications, includes of course implant fracture, which is considered a severe complication requiring extraction of the implant and its supporting bone.[6-9]

A series of recent systematic reviews, based on several clinical studies with at least 5 and 10 year follow up periods, reported a high incidence of such mechanical complications'[1, 9-10] with a 5-year complication rate for a total number of mechanical complications ranging from 16.3%-53.4%. [10] Fracture of the fixation screw is one of the most common mechanical complication, with a 5 and 10 year estimated complication rate of 9.3% and 18.5%, respectively. Implant fracture is considered a severe but rare complication, with a 5 year complication rate of up to 4%.[10] Dhima et al.[11] presented a long-term retrospective study evaluating the outcome of 1325 implant, after a follow up time of 29 years. Mechanical complications were more frequent than biological ones. Well over half (58%) of the implants experienced at least one mechanical complication. The study also showed that mechanical complications occur significantly later than biological complications, with a mean time of 5 years for biological complications to occur versus 7.6 years for mechanical complications. Fracture of the fixation screw (8.5%), and abutment fracture (5.5%) were the top observed mechanical complications.

Regarding implant fracture, 6% of the lost implants are the result of implant fracture, according to Manor et al.[5] In parallel, Pommer et al. [12] recently published a systematic

review meta-analysis on the incidence of implants' fracture, reviewing a large number of clinical studies that reported such fractures. Their study estimated an incidence of implant fracture to be 2.8% after a follow up time of 8 years. Most fractured implant included in this study occurred just after a mean time of 4.1±3.5 years. These incidences clearly highlight the *importance of the follow up time* on the occurrence of implant fracture.

All these studies, dealing with implant loss and implants complication rates, have clearly pointed out that mechanical complications, and among them *implant fracture*, do actually occur with a high incidence rate after long follow-up time periods. Mechanical complications occur significantly later and more frequently than biological complications, and their severity is much more pronounced because of the complexity of treatment that ensues.

The identification of the probable causes leading to mechanical complications is important in order to prevent their recurrence. Mechanical complications can be related to several parameters. The type of restoration supported by the implants, when the type of restoration whether removable or fixed prosthesis, may influence the loads that are transmitted to the implant and thus the incidence of mechanical complications.[3] Occlusal loads' magnitude is a key factor contributing to the load imposed on the implants. Para-function habits such as bruxism and clenching may increase the load magnitude on the implant/ prosthesis system leading to early occurrence of mechanical complications.[13] Aside from the above clinical reasons, mechanical reliability of implants depends also on their overall design, materials used and surface treatments for improved osseointegration. Examining the fracture surface of retrieved fractured dental implants and implant components (fractographic analysis) is the optimal procedure to assess structural integrity. *Metal fatigue* [14] has been identified as the implants' main fracture mechanism by many studies. [8, 15-16] The cause(s) for fatigue crack initiation was first shown to be related to *implant design* that includes significant stress concentrators.[15, 17-18] Accelerated fatigue failure was also observed for implants that were

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cyclically loaded in a saliva-like environment, [19] indicating the potentially adverse effects of the in-vitro atmosphere. Moreover, the surface roughening procedure, aimed at promoting osseointegration [20] was also evaluated as a potentially damaging factor to the mechanical performance and reliability of the implants. Large crater-like areas, sharp edges, dents and scratches, with embedded foreign (ceramic) particles, introduced during the *surface treatment*, were also identified as an additional cause for fatigue crack initiation. [21]

Having addressed the relatively high rate of occurrence of mechanical failures over prolonged periods, one may wonder whether those observed fractures actually initiate at the very late stages of the implant life, or whether small cracks might develop at rather early stages, while going un-noticed during the usual follow-up evaluations, and only seen and diagnosed when the fractured implant leads to complete loss of the prosthesis, and collapse of the rehabilitation procedure. Scanning the surfaces of failed implants, which failed (but did not fracture) due to bone loss and implant's mobility, after prolonged time of use, has never been performed so far. Yet, as will be shown in this paper, scanning the surface of retrieved implants that had to be removed because of purely biological complications, is likely to contain a wealth of new information related to the presence of developing micro-cracks in the structure.

The study reports a thorough scanning electron examination of the surface of 100 late failed implants. The presence of micro-cracks is extensively characterized with regards to their frequency, location on the implant, origin and probable causes.

Materials and methods

Collection of implants

One hundred implants were collected from four private clinics located in Israel. All the implants were extracted most likely due to bone loss and/or lack of bone support. Those are considered as "failed" implants. Unfortunately, no medical record of the failed dental implants was made available, such as implant material, intra-oral location, service years, carried rehabilitation, proximity to additional implants or degree of bone loss. Likewise, no information was available about the patient, such as gender, age, oral status and habits. Consequently and likewise, the implants were investigated on purely technical grounds without addressing the related medical issues. Despite those limitations, the collected implants can be considered as a representative collection of dental implants, without any bias like single manufacturer, or single dental clinic. All the investigated implants share one feature, namely all had to be retrieved because of reasons other than mechanical.

Implants cleaning

The collected implants were covered with debris of bone and organic materials that had to be removed in order to perform a complete reliable examination. All implants were cleaned according to a cleaning protocol described on Table 1 .[16]

Table 1: Proposed cleaning protocol for retrieved dental implants

Layer to be removed	Chemical solution	Time in solution
Blood / soft tissue	Sodium hypochlorite 3%	< 10 min
Organic layer	*Acetone (commercially pure)	30 min
Inorganic layer	**EDTA 17%	As needed

acetone**, organic solvent, ***Ethylenediaminetetraacetic acid, chelating agent, sequester metal ions such as Ca^{2+} and Fe^{3+}

The specimen was inserted in to a 100ml glass beaker. The beaker was filled with the selected chemical solution until the specimen was completely covered by the solution. During the time in the solution, the beaker was kept in a hot water ultrasonic bath. Between solutions, the specimen was thoroughly rinsed with water or ethyl alcohol.

Implants identification

In order to identify the metal composition of the implants, SEM-EDX (energy dispersive X-ray spectroscopy in the scanning electron microscope) analysis was performed. The identification is semi-quantitative, but it allows establishing a clear distinction between commercially pure Ti (CP-Ti) and its alloys.

Implants examinations

All implants were examined for early signs of mechanical failures (e.g. cracks) by using scanning electron microscopy (SEM, Phillips XL 30, Eindhoven, Netherlands). The analysis consisted of thorough surface scanning of the implant on its entire periphery (360°) and length.

For each examined implant, 5 primary properties were evaluated, namely:

1. Characterization of the implants diameter and length,

2. Identification of the surface treatment if any,

3. Presence of defects and their characterization,

4. Identifications of the defects' location,

5. Involvement of embedded foreign particles with the observed defects.

Statistical analysis

Statistical analysis was performed using SAS statistical software, version 9.2 (SAS Institute, Cary, North Carolina) in order to assess potential correlations between the implants'

properties (material, dimensions, surface treatment and involvement of embedded foreign particles), and the observed surface defects and their location.

The correlation between the material composition, implant length, involvement of particles and the observed defects was evaluated using the Chi-square test. The influence of the implant width and surface treatment was assessed using the Fisher exact test, because the asymptomatic Chi-square test was not appropriate (number of positive observations was less than 5). In all tests, the significance level was set to 0.05.

Results

About the implants

The SEM-EDX analyses indicated that 89% of the 100 implants were made of Ti-6Al-4V, and the remaining 11% of CP-Ti.

Next, the surface treatments were identified. It was found that 94% of the implants underwent a specific surface treatment, while the remaining 6% of the implants were as-machined only[22]. The surface treatments were further divided into two groups. The first, coated implants, includes titanium plasma spray (TPS) (30%), or anodizing (1%) The second comprises uncoated implants that underwent grit-blasting and etching (50%), grit blasting only (9%), or etching only (4%). Fig. 1 shows representative SEM micrographs of the 6 typical surface topographies.
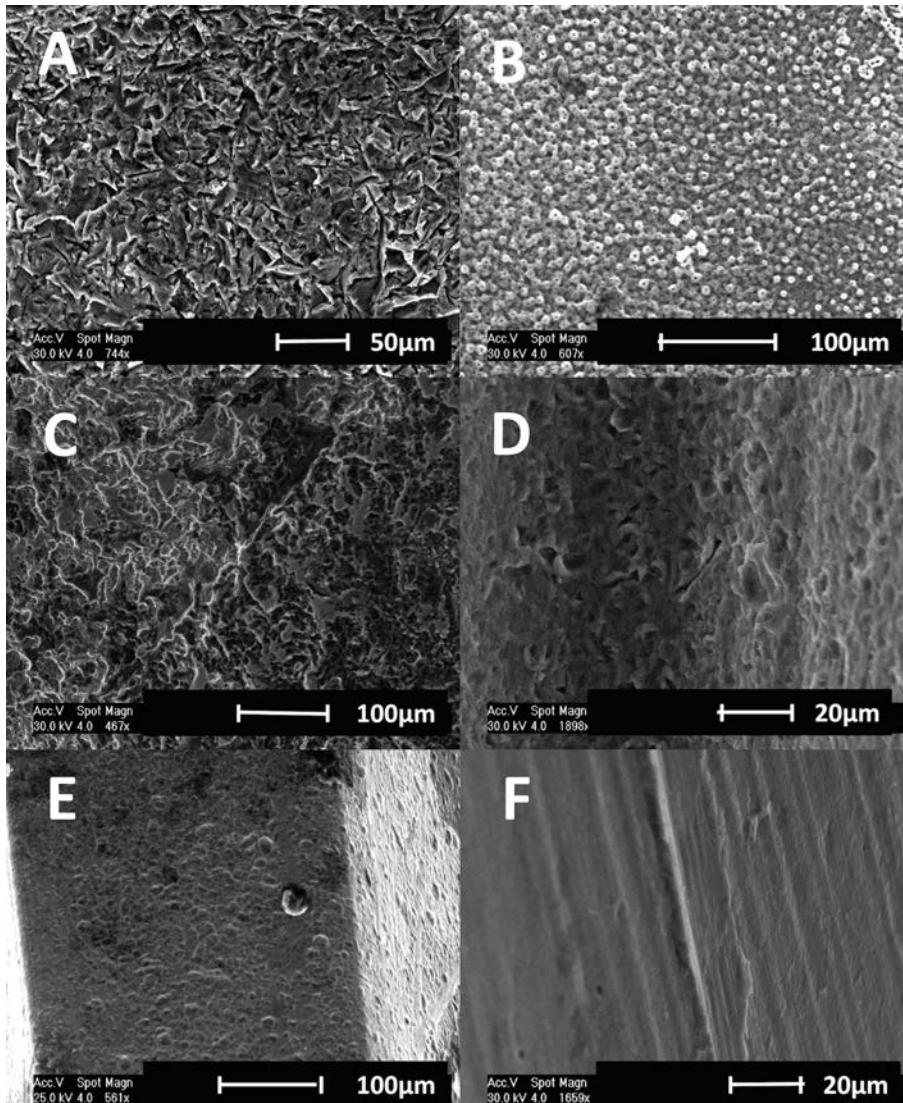
Figure 1: Surface treatments on retrieved implants. A. Titanium plasma spray (TPS). B. Anodizing. C. Grit-blasting and etching. D. Grit-blasting only. E. Etching only. F. As-machined surface.

The diameter and length of each implant were also characterized to define specific groups.

85% of the implants had a standard diameter of 3.6-4.4mm. 6% of the implants were narrow with a diameter of less than 3.5mm, and the remaining 9% were wide, with a diameter exceeding 4.5mm.

27% of the implants were considered short, with a length shorter than 10 mm, and the remaining 73% were longer (10-16 mm).

About the defects

Mechanical defects were identified on the scanned surfaces of the implants. The defects were (arbitrarily) divided according to their length and appearance. Defects that had a length exceeding 0.5mm were defined as "full cracks" (see Fig. 2).
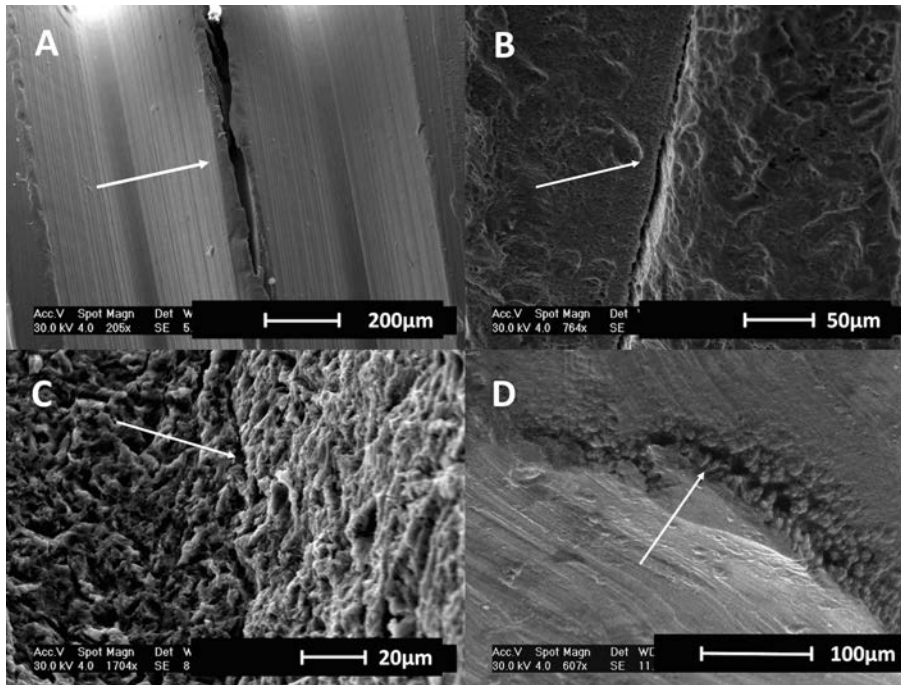

Figure 2: "Full cracks" (white arrows): SEM micrographs of surface defects defined as "full cracks". A. As-machined, B. Grit-blasted and etched, C. TPS, and D. Anodizing. The white arrows mark "full cracks".

Defects with a length between 25µm-100µm were defined as "crack-like defects" (Fig. 3).
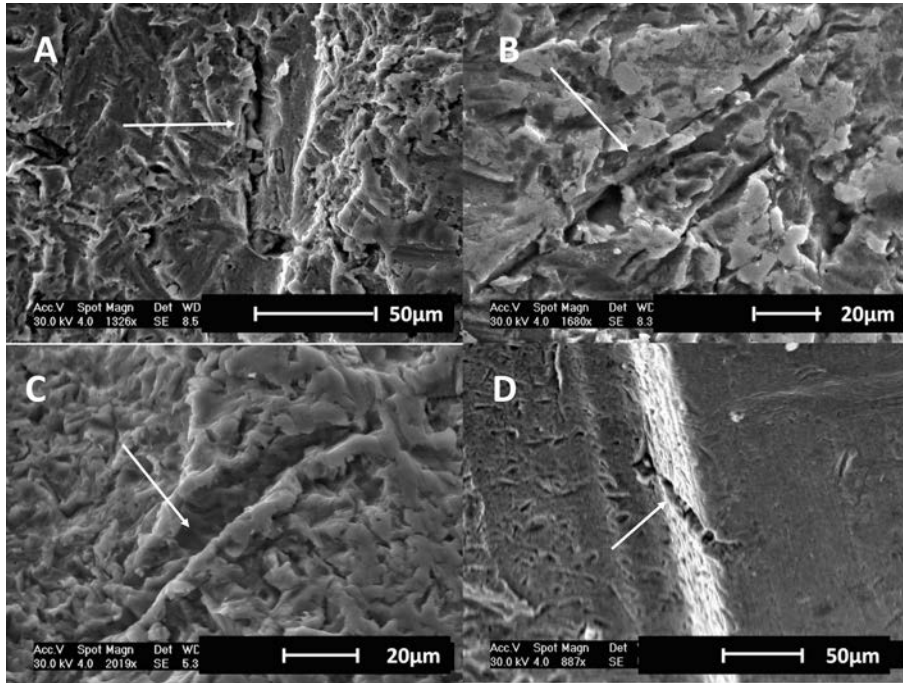
Figure 3: "Crack-like defects (white arrows)": SEM micrographs of surface defects defined as "crack-like" A.and B. Grit-blasted and etched. C. coated TPS. D. Grit-blasted only.

Altogether, 62% of the implants contained defects, of which 28% were full cracks, and 34% were crack-like defects. Surface defects can be generated during the surface preparation treatment, as shown for grit-blasted specimens.[21] However, the observed defects on the examined commercial implants before implantation and loading, were quite abundant, and consisted essentially of craters. This is in contrast with the number and typical morphology of the crack-like defects observed in the present work, which were deeper and wider, as characteristic of full cracks.

In addition, none of the examined implants exhibited signs of gross plastic flow that would unavoidably precede crack/flaw formation in the investigated ductile materials, had they been subjected to overload during implant extraction or insertion. Likewise, no signs of wear or tool markings, all indicative of a surgical procedure, were observed in the vicinity of the defects. It can therefore, be reasonably assumed that the present crack-like defects and full cracks were in fact generated during the implant's use. Finally, note that the defect

classification used here is arbitrary, in the sense that the defects' length is continuously distributed, so that irrespective of their denomination, those are all defects.

As a general remark, one should note that sizing the *depth* of the micro-cracks without prying them open is not possible, and such information is of course quite necessary for fracture-mechanics based calculations. Since most fatigue cracks are semi-elliptical or semi-circular, the depth of the observed cracks can be surmised to be of the order of the measured length L/π, which is a lower bound, considering that the crack-front itself is seldom a straight line.

Implant parameters-defect relationship

Table 2 summarizes all the observed implants parameters and the various identified defects, as well as the statistical significance of the correlation between them.

Table 2: Implant parameters and observed defects (In the second column, the numbers. in parentheses indicate the total number of implants of a kind). GB stands for grit-blasting. N.S. indicates "not significant".

		Defects						P-Value
		Full cracks		Crack like defects		No defects		
		n	%	n	%	n	%	
Implant's material	CP-Ti (11)	8	73	1	9	2	18	P=0.0038
	Ti-6Al-4V (89)	20	22	33	37	36	41	
Surface treatment type	Without coating (GB+etching, GB only and Etching only) (63)	15	24	21	33	27	43	P=0.0060
	Coated(TPS and Anodized) (31)	7	23	13	42	11	35	
	As-Machined (6)	6	100	0	0	0	0	
Implant's width	Narrow <3.5mm (6)	2	33	1	17	3	50	N.S
	Standard 3.6-4.4mm (85)	25	30	30	35	30	35	
	Wide>4.5mm (9)	1	11	3	33	5	56	

Implants length	Short <10mm(27)	8	30	9	33	10	37	N.S
	Long>10mm (63)	20	28	25	34	28	38	
Defect's location	Threads (51)	24	47	27	53	-	-	P=0.025
	Neck (4)	4	100	0	0	-	-	
	Threads and Neck (7)	0	0	7	100	-	-	

Effect of implant material

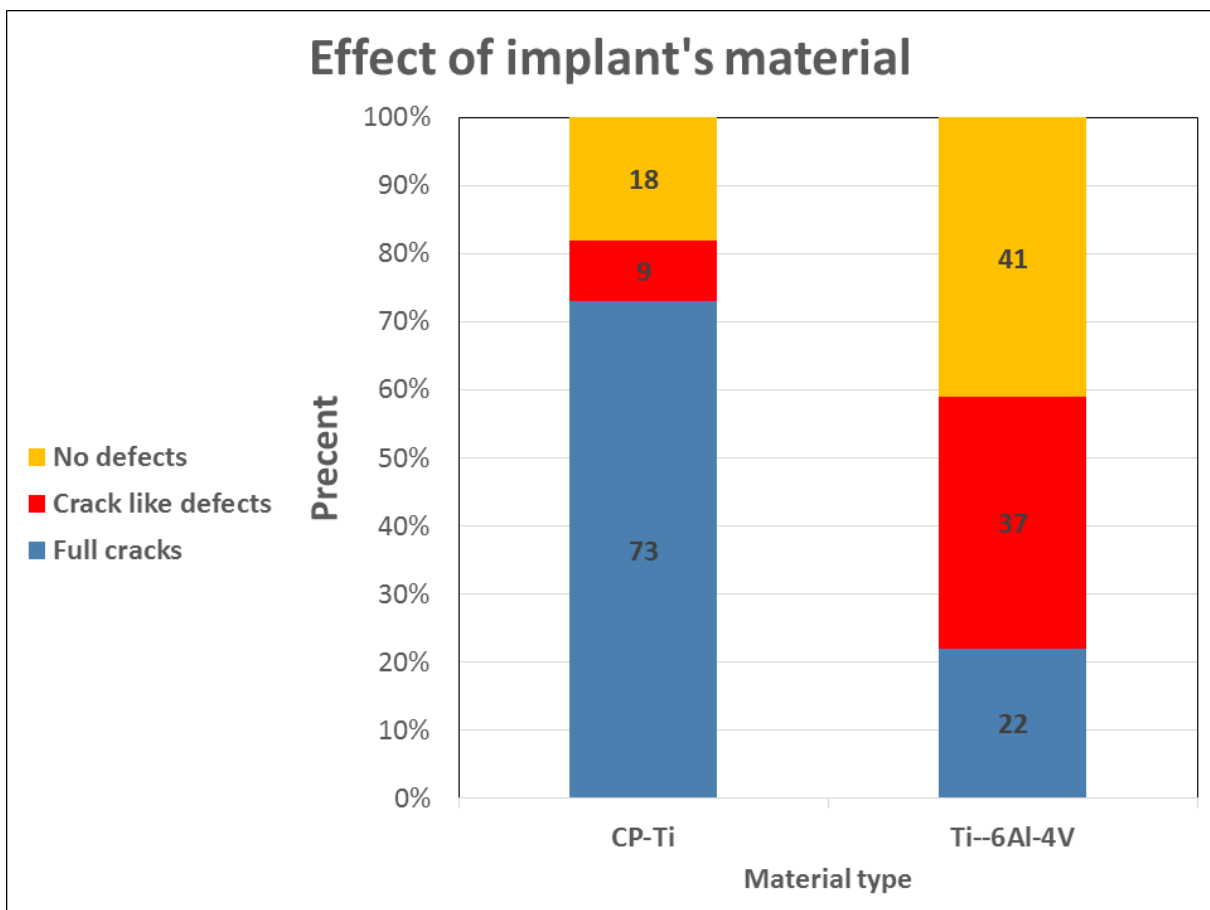Fig. 4 presents the distribution per nature of the defects for the 2 implants' materials (Table 1).

Figure 4: Effect of the implants' material on the various identified defects.

The statistical analysis reveals that there is a definite correlation between the implant's material and the frequency and nature of observed defects (P= 0.038). This observation might

indicate that CP-Ti is more prone to developing mechanical damage. This may be based on the fact that, for a similar geometry and mastication loads, the relative (normalized by yield strength) stress is lower for the stronger Ti alloy as compared to the CP-Ti. Lower cyclic stresses are known to confer a longer overall structural fatigue life.

Effect of surface treatment

Fig. 5A shows the distribution of the defects per surface treatment, while Fig. 5B considers the three above-defined groups, namely as-machined, coated and without coating.
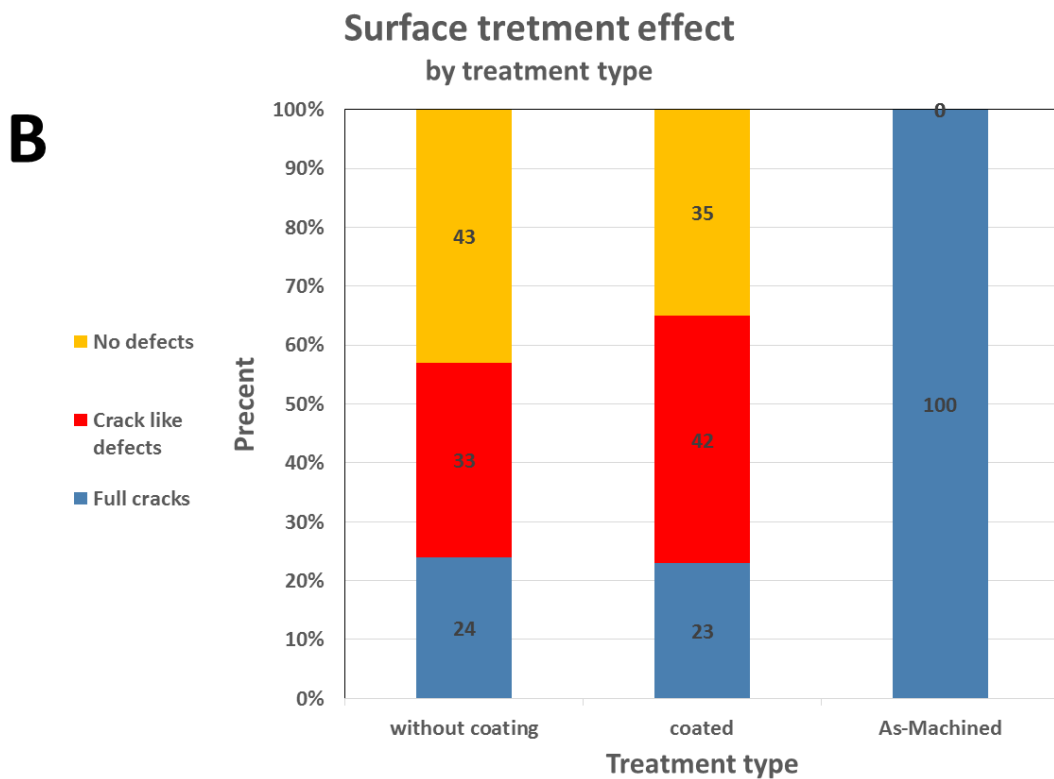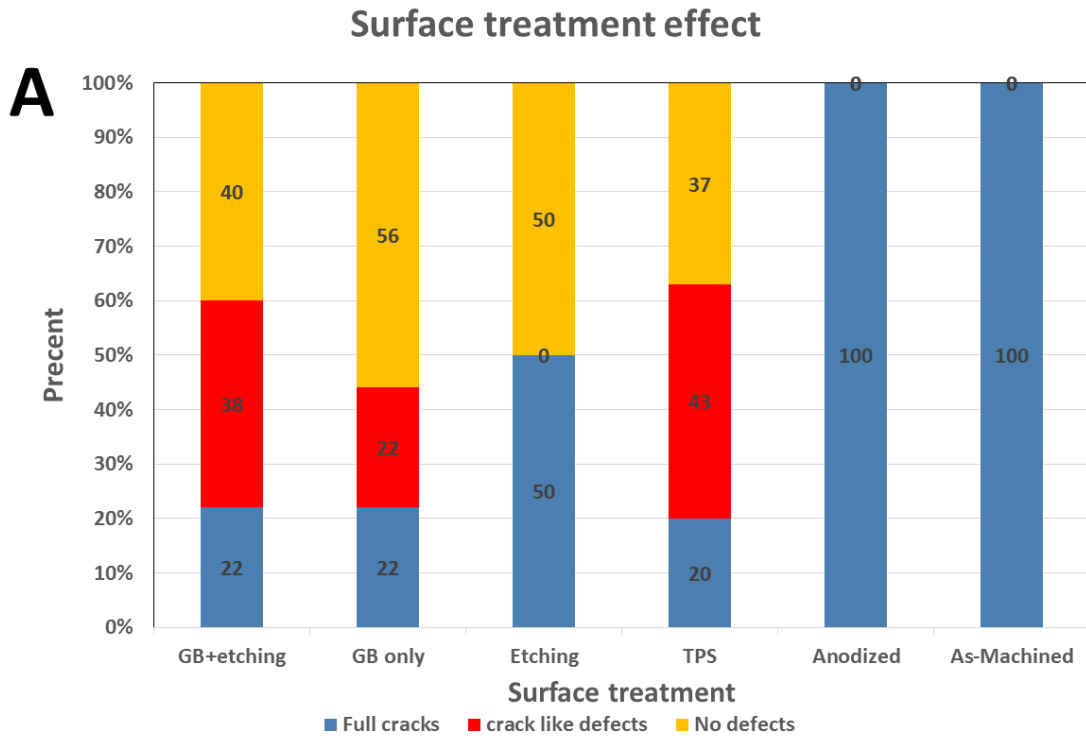
Figure 5: Effect of the implants' surface treatments on the various identified defects A. Distribution of the defects per surface treatment. B. Distribution of the defects per surface treatment type (e.g. coated, uncoated and as-machined). Be consistent and put a capital Without..Coated..Pse correct treatment in the title

The following statistical analysis considers the relationship between the type of surface treatment and the observed defects (as shown in Fig. 5B). Here, a definite correlation exists (P=0.006). However, when "coated" and "without coating" implants are compared in terms of defects, it is found that there is no significant difference between those groups.

Those results are probably related to the fact that as-machined implants are no longer manufactured today, and the collected as-machined implants were most likely retrieved after a longer service time, therefore with a higher probability for containing cracks. This supports defect causation with function rather than during handling or placement.

Examination of the grit-blasted (with or without etching) implants further revealed the presence of embedded foreign particles in both crack-like defects and full cracks alike, as exemplified in Fig. 6.
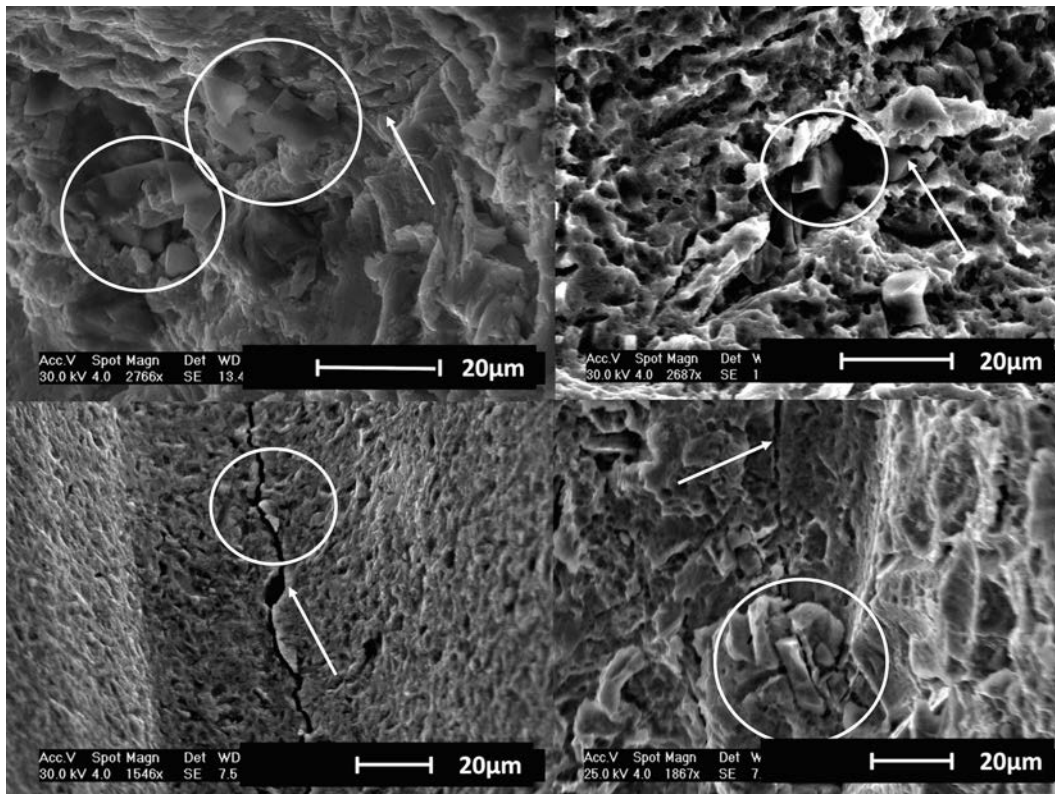
Figure 6: Embedded foreign particles on full cracks and crack-like defects, as identified on grit-blasted (with or without etching) implants. The white arrows mark the defects (full cracks or crack-like defects) and the white circles indicate embedded foreign particles.

Among implants that underwent grit-blasting surface treatment (e.g. GB+etching and GB only), 85% of full cracks (11/13) and 76% of crack-like defects (16/21) showed involvement of embedded foreign particles. No statistical correlation was found between the involvement of embedded foreign particles and the type of defects (full cracks or crack-like defects) ($P \gg 0.05$). This points to the same probability of finding embedded foreign particles in full cracks as in crack-like defects. In other words, this result shows that the particles' involvement is the same from the "early" crack-like defects stage to the later stage of full grown cracks.

Effect of implant design

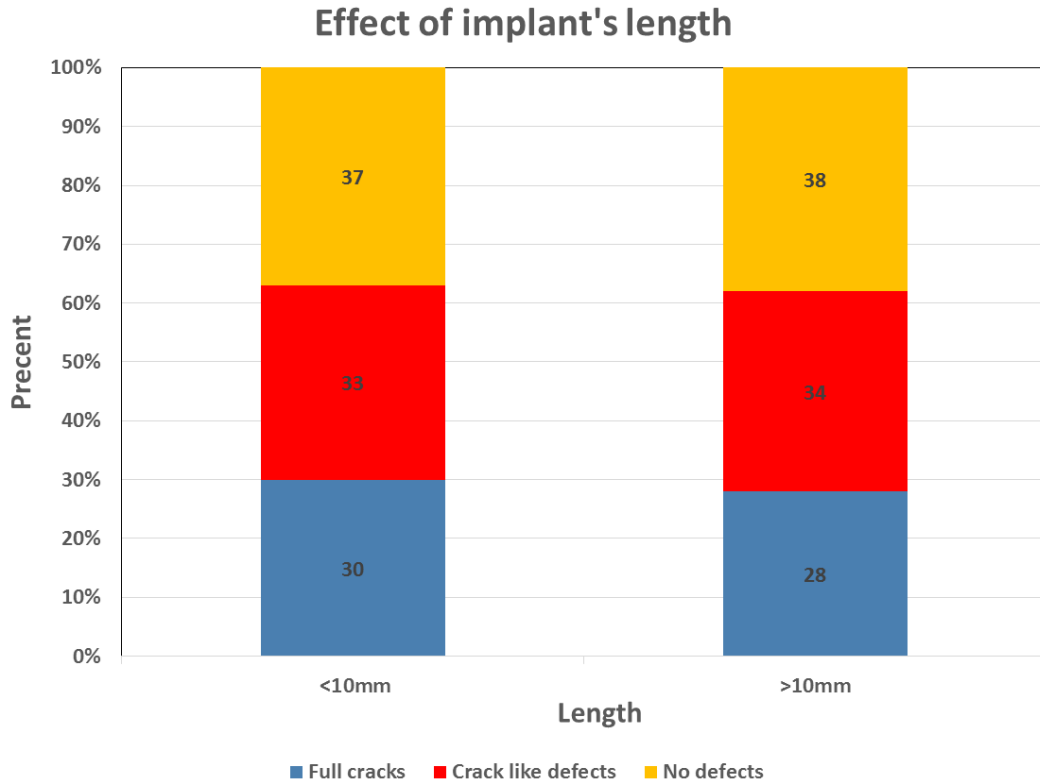Fig. 7 shows the distribution and nature of observed defects for implants of variable length (7A) and diameter (7B).
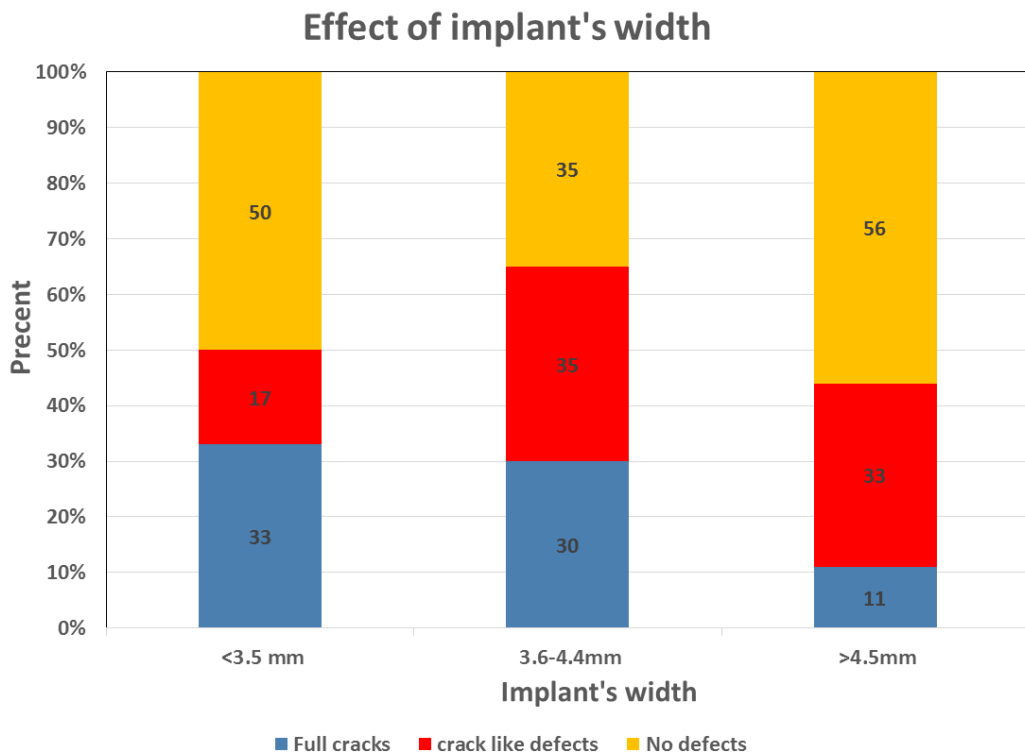
Figure 7: Effect of the implants' design on the various identified defects A. Effect of length B. Effect of diameter.

For both the length and width parameters, the statistical analysis indicates an apparent lack of

correlation (p>>0.05) in terms of defect types.

About defect location

The observed defects were further divided according to their location. For this purpose, 3 specific groups were identified in the implants: neck, thread, and both neck and threads. Table 2 indicates the distribution of defects according to their location. A definite correlation exists (P=0.0025) between the defects location and the defect type. Although most defects were observed on the implant's threads, all the defects that were observed on the implant's neck were full cracks, pointing to the implant's neck as the potentially preferential site for failure.

Discussion

The present research is based on the selection of a random sample of 100 implants. As was shown, those implants are made of two different materials, have undergone different surface preparation treatments, and have different diameters and lengths. Therefore, this sample can be considered as representative of a wide variety of implants used in clinical implant dentistry.

Unfortunately, data about the duration of service of those implants was unavailable as well as their placement region (anterior vs. posterior), and their prosthesis construction (cantilever vs. supported beam). As a result, the statistical meaning of the reported observations cannot be ascertained beyond the examined sample. Despite that, it is clear from the observed bone residues covering the implants surface that those implants were all fully osseointegrated before, and failed probably due to progressive loss of bone support or biological complication. None of them failed due to mechanical complications such as cracks or full fracture.

As such, those implants can be considered from a mechanical point of view as "*in-vivo*" implants that went through real life repeated loading, therefore perfectly suitable to study the effect of mastication and the oral environment on their mechanical integrity.

The clear novelty of this analysis is that a very large percentage of the retrieved implants contains various grades of defects, ranging from crack-like to full cracks. Depending on time, crack-like defects, which can be regarded as a stress concentration, have a high probability of developing into full cracks. Once present, the crack-like defect may likely grow into a single structural crack, due to the repeated character of mastication loads (fatigue), by coalescing with other crack-like defects until a full main crack is formed. In that respect, the crack-like defect is the embryo of the future crack that will grow with time and lead to implant fracture.

Implants' material is usually chosen for its combination of biocompatibility and mechanical strength. This study indicates that for the two identified materials, namely CP-Ti and Ti6Al4V alloy, given the mechanical design constraints of the implants, both have a marked tendency to cracking. Even so, the present results and statistical analysis seem to indicate that the Ti6Al4V alloy, with a higher tensile strength (therefore experiencing lower cyclic relative stresses), possesses a higher resistance to cracking than CP-Ti. A stronger statement would necessitate a controlled experimental study.

Surface treatments are selected to optimize osseointegration. A great variety of surface treatments exist today, in order to achieve a desired degree of surface roughness.[22] In this study, all the various surface treatments were found to contain at least crack-like defects. If one does not consider the obsolete type of as-machined implants, no statistically meaningful difference between the various surface treatments could be identified. It can nevertheless be concluded here that the desired degree of surface roughness that will improve osseointegration, be it achieved either through coating or grit-blasting, might also promote the

adverse effect of cracking, a fact that is well known as stress concentration effect in solid mechanics[23].

Moreover, we observed that, in implants subjected to a grit-blasting treatment (with or without etching), numerous embedded foreign particles were associated with crack-like defects or full cracks. In addition to the very high involvement of the particles in the incidence of defects (>75%), no further statistical correlation was found between their presence in crack like defects and full cracks. Crack-like defects can be regarded as crack embryos (preferential site) for fatigue crack nucleation. Our results show that the proportion between the defect type and the particles presence is constant, without significant statistical difference. This suggests that the same proportion of crack-like defects, caused by impact of foreign particles, is likely to evolve into later full cracks with minimal involvement of additional fatigue cracks originated for other than particle-related reasons. This observation further strengthens the relation between cracks and foreign particles, from the nucleation to growth stages. Those findings are fully consistent with previous work [21, 24] which singled out the potentially deleterious effect of embedded foreign particles on the development of fatigue cracks.

In this context, note that Shemtov-Yona et al.[21] presented a fractographic analysis of 15 retrieved fractured CP-Ti and Ti-6Al-4V dental implants, and identified fatigue as the main fracture mechanism. When the surface of the implants was examined, numerous secondary cracks were identified in the vicinity of the main crack. These secondary cracks did not lead to the final fracture, but they did also reveal the relationship of the secondary cracks to the fracture surface topography (roughness), and to embedded ceramic particles, which resulted from the grit-blasting surface treatment.

Examining the effect of implant's design (diameter and length) on the identified defects, our results show that both the length and the width of the implants have apparently no substantial

influence on their mechanical integrity. The effect of implant diameter was previously studied "in-vitro",[17] where narrow implants exhibited a lower fatigue strength and earlier failure. In that context, one should note, that a higher incidence of implant fracture has been reported in narrow implants.[25] The current results do not confirm those observations when the two implant materials are considered together, but it must be kept in mind that each implant has its own mechanical history, as opposed to carefully controlled fatigue testing, as e.g in [17].

All in all, the reported results, which result from (random) observations rather from clinically planned experiments, indicate one previously unreported observation. Namely, a total of 62% of the apparently intact retrieved implants were flawed to various extents, all flaws that indicate a strong potential for future fatigue fracture of the implant. One may wonder how it is that such a large number of early fractures, as shown here, does not come into account when considering the low incidence of reported implant fracture. This apparent contradiction can only be explained by the fact that all the investigated implants in this work were extracted due to reasons that are not related to their mechanical performance. Biological failure and its consequences clearly act as a "fuse" that avoids future potential mechanical failure. All the more so when the retrieved implants are not examined the way they were in this study. More important, the present observations might hint that once the occurrence of biological failures will be significantly reduced, the incidence of implants fracture is likely to increase as they will be given an opportunity to develop.

Conclusions

Mechanically sound dental implants were retrieved because of biological complications. Examination of 100 implants' surfaces and characteristics revealed the following:

- About 60% of the examined implants contained crack-like defects or full cracks.

- CP- Titanium implants were more damaged than Ti-6Al-4V implants.

- When surface roughening included grit blasting, the involvement of embedded foreign particles was evident, and a strong connection to the defects evolution was seen, as noted in previous work[21].

- No correlation between the implants' width and length and defect occurrence or nature was identified.

- Because biological failures occur firstly, they don't allow for later mechanical failures of earlier in-vivo damaged implants.

- The present observations suggest that the occurrence of mechanical failures of dental implants is likely to increase as the frequency of biological failures that necessitate implant extraction will diminish.

Acknowledgment

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Figure legends

Figure 1: Surface treatments on retrieved implants. A. Titanium plasma spray (TPS). B. Anodizing. C. Grit-blasting and etching. D. Grit-blasting only. E. Etching only. F. As-machined surface.

Figure 2: "Full cracks": SEM micrographs of surface defects defined as "full cracks". A. As-machined, B. Grit-blasted and etched, C. TPS, and D. Anodizing. The white arrows mark "full cracks"

Figure 3: "Crack-like defects": SEM micrographs of surface defects defined as "crack-like" A.and B. Grit-blasted and etched C. coated TPS D. on Grit-blasted only. The white arrows mark "crack-like defects.

Figure 4: Effect of the implants' material on the various identified defects.

Figure 5: Effect of the implants' surface treatments on the various identified defects A. Distribution of the defects per surface treatment B. Distribution of the defects per surface treatment type (e.g. coated, uncoated and as-machined)

Figure 6: Embedded foreign particles on full cracks and crack-like defects, as identified on grit-blasted (with or without etching) implants. The white arrows mark the defects (full cracks or crack-like defects) and the white circles mark embedded foreign particles.

Figure 7: Effect of the implants' design on the various identified defects A. Effect of length B. Effect of diameter.

Table 1: Proposed cleaning protocol for retrieved dental implants.

Table 2: Implant parameters and observed defects (In the second column, the numbers. in parentheses indicate the total number of implants of a kind). GB stands for grit-blasting. N.S. indicates "not significant".