UNIVERSITAT DE BARCELONA

Mechanical resistance to fracture of narrow platform dental implants with hexagonal external connection submitted to implantoplasty with different bone levels and crown/implant ratios. An in vitro study.

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Mechanical resistance to fracture of narrow platform dental implants with hexagonal external connection submitted to implantoplasty with different bone levels and crown/implant ratios. An *in vitro* study.

Doctoral thesis report by **Bruno Alexandre Morais Leitão de Almeida** to apply for the doctoral degree from the Universitat de Barcelona

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March, 2022

DECLARATION OF CONFORMITY FOR PRESENTATION

UNIVERSITAT DE BARCELONA

Prof. Eduard Valmaseda Castellón, Professor of the Faculty of Medicine and Health Sciences of the Universitat de Barcelona and Prof. Rui Figueiredo, Professor of the Faculty of Medicine and Health Sciences of the Universitat de Barcelona,

CERTIFY that: The work entitled: " Mechanical resistance to fracture of narrow platform dental implants with hexagonal external connection submitted to implantoplasty with different bone levels and crown/implant ratios. An *in vitro* study.", presented by Bruno Alexandre Morais Leitão de Almeida as a Doctoral Thesis; has been carried out under our direction in the Department of Odonto-Stomatology of the Universitat de Barcelona and corresponds faithfully to the results obtained. This Doctoral Thesis has been thoroughly reviewed by us and we consider that it meets the requirements to be presented to obtain the Degree of Doctor of Dentistry in front of a panel of experts designated by the University.

And, for the record and in compliance with current provisions, we sign this certificate.

Prof. Dr. Eduard Valmaseda Castellón.
Professor, Universitat de Barcelona

Prof. Dr. Rui Figueiredo.
Professor, Universitat de Barcelona

Barcelona, December 20th, 2021.

“The beautiful thing about learning is that nobody can take it away from you.”

B.B. King

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GLOSSARY

Glossary

ANOVA: Analysis of variance.

BL: Bone loss.

BOP: Bleeding on probing.

CIR: Crown-to-implant ratio.

CP: Commercially pure.

$F_{max.}$ Maximal compression force.

IP: Implantoplasty.

ISO: International Organization for Standardization.

mm: millimetre.

N: Newton

PI: Peri-implantitis.

PTFE: Poly-tetra-fluoro-ethylene

PUBLICATIONS

The thesis entitled "**Mechanical resistance to fracture of narrow platform dental implants submitted to implantoplasty with different bone levels and crown/implant ratios. An *in vitro* study.**" is presented in the form of compendium of scientific publications and includes two papers, as follows:

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ABSTRACT

Abstract (English)

Title: Mechanical resistance to fracture of narrow platform dental implants submitted to implantoplasty with different bone levels and crown/implant ratios. An *in vitro* study.

Introduction: Peri-implantitis is an inflammatory condition that affects soft and hard tissues around dental implants and that can lead to implant failure. Implantoplasty is a procedure that allows implant surface decontamination by removing the implant threads and smoothening its surface, thus limiting disease progression. Bone loss associated with peri-implantitis will increase the clinical crown-to-implant ratio which, in turn, has been reported to decrease implant resistance.

Hypothesis: Implantoplasty significantly reduces implant width and therefore decreases its resistance to fracture, especially in the implant platform area. Moreover, lower bone levels and higher crown-to-implant ratios negatively affect the resistance to fracture of external connection 3.5-millimeter-wide platform implants with and without implantoplasty.

Objectives: To determine the effect of implantoplasty in the mechanical resistance and implant width reduction of external connection 3.5-millimeter-wide platform implants; To determine if different bone levels and crown-to-implant ratios affect the resistance to fracture of external connection 3.5-millimeter-wide platform implants with or without implantoplasty and which part of the implant is more susceptible to fracture.

Methodology: Two *in vitro* resistance to fracture tests using 15-millimeter-long and 3.5-millimeter-wide platform implants with hexagonal external connection were conducted according to UNE-EN ISO 14801:2016. In the first test, 3 different crown-to-implant ratios (abutment heights of 7.5 millimeter (mm), 11.25mm and 15mm) were tested considering implants with 50% of bone loss. A total of 48 implants with (n=24) and without (n=24) implantoplasty were divided into 6 different subgroups. In the second

resistance to fracture test, a total of 32 implants with 2 different bone loss levels (3mm; 7.5mm), with (n=16) and without implantoplasty (n=16), were analyzed. The primary outcome variable for both tests was the maximal compression force. A descriptive and bivariate analysis of the data was performed.

Main results: Implantoplasty significantly reduced the width of the implant wall ($p<0.05$) in all reference points and in both experiments. The maximal compression force was significantly higher for both control and implantoplasty samples in 2:1 crown-to-implant subgroup compared with the 2.5:1 and the 3:1 samples ($P<0.001$). Greater bone loss also decreased the maximal compression forces, although this association was only significant for the control implants ($p=0.001$).

Implantoplasty and control implants had similar maximal compression forces when considering the mean total values in both resistance to fracture tests.

Both experiments showed that most fractures were located in the platform area.

Conclusions: Implantoplasty significantly reduces implant width and this does not seem to significantly affect the resistance to fracture of external connection 3.5-millimeter wide implants. Bone loss and clinical crown-to-implant ratio seem to be more relevant variables when considering the fracture resistance of dental implants. Platform fractures are the most frequent in this test conditions.

Resumen (Castellano)

Título: Resistencia mecánica a la fractura de implantes dentales de plataforma estrecha sometidos a implantoplastía y con diferentes niveles óseos y ratios corona/implante. Estudio *in vitro*.

Introducción: La periimplantitis es una patología inflamatoria que afecta a los tejidos duros y blandos periimplantarios y que puede provocar el fracaso del implante. La implantoplastia es un procedimiento que permite la descontaminación de la superficie del implante, eliminando sus espiras y reduciendo su rugosidad. La pérdida ósea asociada a la periimplantitis aumenta el ratio corona-implante que, a su vez, puede reducir la resistencia del implante.

Hipótesis: La implantoplastia reduce significativamente la anchura del implante y, por lo tanto, su resistencia a la fractura, especialmente en la zona de la plataforma. Además, un nivel óseo más apical y un ratio corona-implante más elevado afectan negativamente a la resistencia a la fractura de implantes con conexión externa, de 3.5 milímetros de diámetro con y sin implantoplastia.

Objetivos: Determinar el efecto de la implantoplastia sobre la resistencia mecánica y sobre la reducción de la anchura de implantes con conexión externa y con una plataforma de 3.5 milímetros. Determinar si los diferentes niveles óseos y ratios corona-implante afectan a la resistencia a la fractura de implantes con conexión externa y con una plataforma de 3.5 milímetros con o sin implantoplastia y evaluar qué zona es más susceptible de fracturarse.

Metodología: Se realizaron dos ensayos de resistencia a la fractura *in vitro* según la norma UNE-EN ISO 14801: 2016, utilizando implantes de 15 milímetros de longitud con conexión externa hexagonal y con una plataforma de 3.5 milímetros de anchura. En la primera prueba, se evaluaron 3 ratios corona-implante (alturas de pilar de 7.5 milímetros

(mm), 11.25 mm y 15 mm) en implantes con 50% de pérdida ósea. Un total de 48 implantes con (n = 24) y sin (n = 24) implantoplastia fueron divididos en 6 subgrupos diferentes. En la segunda prueba de resistencia a la fractura, se analizaron un total de 32 implantes, con (n = 16) y sin implantoplastia (n = 16), con 2 niveles de pérdida ósea (3 mm; 7.5 mm). Se estableció como variable respuesta principal la fuerza máxima de compresión. Se realizó un análisis descriptivo y bivariable de los datos.

Resultados principales: La implantoplastia redujo significativamente la anchura de las paredes del implante ($p < 0.05$) en todos los puntos de referencia y en ambos estudios. La fuerza de compresión máxima fue significativamente mayor para las muestras de control y de implantoplastia en el subgrupo ratio corona/implante 2:1 en comparación con las muestras de los demás subgrupos (ratios corona/implante 2.5:1 y 3:1 ($P < 0.001$)). Una mayor pérdida ósea también disminuyó las fuerzas de compresión máximas, aunque esta asociación solo fue significativa para los implantes del grupo control ($p = 0.001$).

Los implantes sometidos a implantoplastia y los implantes del grupo control tuvieron una compresión máxima similar al considerar los valores totales medios en ambas pruebas de resistencia a la fractura.

La mayoría de las fracturas se ubicaron en el área de la plataforma en ambos ensayos.

Conclusiones: La implantoplastia reduce significativamente el diámetro del implante aunque no parece afectar significativamente la resistencia a la fractura de los implantes de conexión externa de 3.5 milímetros. La pérdida ósea y el ratio clínico corona-implante parecen ser variables más relevantes cuando se considera la resistencia a la fractura de los implantes dentales. Las fracturas de plataforma son las más frecuentes en las condiciones de prueba.

INTRODUCTION

Introduction

.1 Dental implant history

The first use of dental implants was documented in the Mayan civilization around 600 AD. Pieces of shells, stone and ivory were used by ancient cultures as a replacement for mandibular teeth, with a similar concept to the one later used for blade-shaped dental implants (1,2). However, these reports of ancient dentistry are still matter of debate amongst investigators (3). Throughout the XIX century, gold, silver, porcelain and iridium were used as materials for dental implants and in the beginning of the XX century, following the success of a chromium-cobalt alloy implant used for hip replacement, Drs. Alvin and Moses Strock are thought to have placed the first successful endosteal dental implant (4). The first patent for a threaded cylindrical endosseous implant was presented in 1938 in the United States of America. Formiggini and Zapponi developed this concept and introduced a post-type spiral endosseous stainless steel implant in the 1940´s (5). Around the same time, in Sweden, sub-periostal implants were being developed by Dahl and later on by Gershkoff and Goldberg, Weinberg, Lew, Bausch and Berman (6). Through the 1960´s and 1970´s, several one-piece implant designs and materials were presented to the scientific community: Cherchieve developed a double-helical cobalt-chromium alloy implant, Linkow used a flat blade-shaped implant (7) and Sandhaus developed a crystallized bone screw made of aluminium (6).

Today, it is possible to find some patients with these types of implants. However, the clinical outcomes and data of early dental implant designs was often poor, leading to unpredictable results. Indeed, few professionals recommended these early innovations (8).

In the sixties, Brånemark, an orthopaedic surgeon realised that titanium chambers placed in rabbit´s tibia for 6 months became firmly attached to the bone and could not be easily removed. This led to the development of the osseointegration concept as a direct structural and functional connection between ordered, living bone and the surface of an implant. Based on these findings, Brånemark developed and tested a two-stage threaded titanium root-form dental implant (6). Briefly after, André Schroeder, from Bern University, provided histological data that proved the existence of direct bone-to-implant contact (9).

.2 Osseointegration process

Osseointegration is achieved by a process of primary bone healing in which a scaffold of woven bone, associated with an expanding vascular net, invades the granulation tissue of the newly formed blood clot uniting bone to an implant surface. Primary bone healing is activated by any lesion of the pre-existing bone matrix that can set free non-collagenous proteins and growth factors activating bone repair. Osseo-progenitor cells of the bone marrow, endocortical and periosteal envelope migrate into the site of the lesion using chemotaxis, proliferating and differentiating into osteoblasts precursors and osteoblasts. Three stages are commonly addressed when describing osseointegration: incorporation by woven bone formation; adaptation of bone mass to load (lamellar and parallel-fibered bone deposition) and adaptation of bone structure to load (bone remodelling) (10). This way, the initial mechanical stability which is influenced by many factors such as implant macro-design, implant surface or local bone characteristics is replaced by a secondary biological stability that relies on the biological process of osseointegration (11).

Albrektsson et al. (12) established the criteria for successful osseointegration: 1) absence of persistent signs/symptoms such as pain, infection, neuropathies, paraesthesia, and violation of vital structures; 2) implant immobility; 3) no continuous peri-implant

radiolucency; 4) negligible progressive bone loss (less than 0.1 mm annually) after the initial physiologic remodelling that occurs during the first year in function; and 5) patient/dentist satisfaction with the implant supported restoration(s) (12,13). Like in natural teeth, it is critical to perform periodical assessments of these parameters, particularly in patients at high-risk of implant loss.

Over the last decades, dental implant therapy has become the treatment of choice to replace missing or hopeless teeth. It is estimated that in 2026, approximately 1 out of every 4 Americans, may have at least 1 implant in place (14).

The success rate of this treatment option has been evaluated in several reviews and a 95-98% success rate is expected over a 5-year period (15–17).

.3 Materials used for dental implant manufacturing

Titanium and titanium alloys

The material of choice for oral endosseous implants has been, and still is, commercially-pure (CP) titanium and titanium alloys (18). These materials are biologically inert, have the ability to bond with osteoblasts, are biocompatible and have adequate mechanical and thermal properties (19).

CP titanium is graded from 1 to 4 according to its resistance to corrosion, ductility and strength. Most dental implants are made out of CP grade 4 titanium and therefore have limited mechanical properties with an elasticity modulus of 104 GN/m^2, a maximum resistance to tension of 240-550 MN/m^2 and the ability to stretch up to 15% before fracture (20). Alloying the titanium with different elements increases the resistance to corrosion, increases the elasticity modulus and improves the machinability and processing capacity (19). Grade 5 titanium alloy (Ti6Al4V) has greater yield strength and

fatigue properties in comparison with CP titanium, being particularly suitable for dental applications. It is composed of 6% aluminium, 4% vanadium, 0.25% iron, 0.2% oxygen and 90% titanium. It has a elasticity modulus of 117 GN/m^2 and a tensile strength of 869-896 MN/m^2(21). Grade 5 alloy is superior to CP forms when it comes to corrosion resistance, fatigue strength and elastic modulus (22). On the other hand, this alloy has been reportedly associated with slow release of vanadium and aluminium ions into the bloodstream and urine, which might trigger a potential inflammatory response activation and neurotoxicity (23). This limitation indicates the need to develop other alloys with better biocompatibility.

Zirconia

Zirconia (crystalline zirconium dioxide) seems to be a valid alternative material to manufacture dental implants due to its high flexural strength of 900-1200 MPa, its hardness of 1200 Vickers, its high resistance to corrosion, its optimal thermal properties and a low susceptibility to adhesion of bacterial biofilm (22). Furthermore, it is a highly aesthetic material that can be especially suitable for patients with thin gingival biotypes that require anterior implant placement or that have a high aesthetic demand. *In vitro* testing suggests that zirconia implants are able to withstand a simulated 5-year period of physiological oral masticatory forces (24). Also, its bone-to-implant-contact is excellent, as reported for titanium implants (25,26).

On the other hand, a systematic review showed that zirconia implants were inferior to titanium dental implants regarding survival and success rates (survival rate of 74-98% after 12 to 56 months and success rates between 79.6-91.6%, 6 to 12 months after prosthetic restoration placement) (27). More recently, a review corroborated these

findings and highlighted the need for long-term evidence on clinical performance of such type of dental implants (28).

Failure resulting from fracture of the material is still reported as a critical factor for usability and clinical acceptance, particularly because implant fractures usually require implant removal. Hence, although promising results have been achieved with two-piece zirconia dental implants, further research is needed to evaluate if this material can replace the standard titanium dental implants (29).

.4 Dental Implant surfaces

The use of machined implants was the benchmark for many years following Branemark original protocol. However, with the intention of increasing bone-to-implant contact and enhancing the osseointegration process, new implant surfaces have been developed (11). The use of micro-rough surface topography on dental implants reduces the extent of fibrous encapsulation and improves the biomechanical properties of the implant-bone interface by improving the micro-mechanical interlock. It is clear that machined titanium surfaces promote bone formation but the adaptation of the bone to that surface includes an amorphous zone thus decreasing the previously described interlock phenomena (30).

It has been reported that a surface roughness of 1-2μm is beneficial for the biomechanical anchorage and biomechanical stability of dental implants enhancing bone cell differentiation, growth, attachment and increasing mineralization (31,32). On the other hand, implants with rougher surfaces (2.35μm) showed a 20% increased risk of developing peri-implantitis (PI) after 3 years in function when compared to machined Brånemark implants (33). This relation between rough surfaces and the onset and progression of peri-implant diseases has been addressed in the literature (34–37).

An implant surface can be altered by addition (creating bumps) or reduction (creating pits and holes). Examples for addition process include the coating of the surface with hydroxyapatite or calcium phosphate, titanium plasma spray and ion deposition. The subtractive methods include mechanical or electrical polishing, grit blasting, acid etching, oxidation or a combination of the previous (32,38). All these strategies aim at inducing a faster osseointegration and avoid a fibrous encapsulation. On the other hand, there have been concerns that procedures like grit blasting may evoke surface micro-cracks that can be the origin of fatigue cracks (39).

Regardless of the dental implant material (CP titanium, titanium alloy or ceramics), surface modifications have an important impact on osseointegration, since the surface chemistry and topography seem to play a critical role in early and late response of the hard tissues (11,40).

.5 Complications in oral implantology

A large array of complications may happen with oral implant rehabilitations: implant loss, sensory disturbance, soft tissue complications, PI and bone loss (BL), implant fracture and technical complications related to implant and prosthetic components, among others. Berglundh et al. (17) performed a meta-analysis on the incidence of biological and technical complications in implant dentistry and concluded that implant loss prior to functional loading is expected to occur in about 2.5% of the cases. On the other hand, implant loss during function occurs in about 2-3% of implants supporting fixed restorations and in about 5% of those supporting overdentures over a 5-year period. These authors found limited information regarding the occurrence of PI, BL and sensory disturbances and also stated that implant fracture is a rare complication occurring in less than 1% of implants during a 5-year period.

Many studies have identified several reasons for implant failures. Mechanical issues, biological pathologies, iatrogenic causes and phonetical, aesthetic or psychological problems are some of the most important aetiologies for unsuccessful treatments (15,41).

Mechanical complications

Mechanical complications can occur to the implant, to its components or to the prosthesis (39). The lack of a metal framework in overdentures, cantilevers over 15mm when using fixed full-arch prosthesis, bruxism, increased length of the rehabilitation and a previous history of mechanical complications have been reported to be risk factors for this kind of complications (42).

Implant, components, abutment and prosthetic screw

The implant platform, where the prosthetic abutment usually seats, provides resistance to axial forces. A non-rotational indexing feature is introduced either on the platform (external connection) or inside the implant body (internal connection). The external hexagonal connection has been introduced several decades ago and might have different dimensions according to the implant manufacturer (43). Different connections can have an impact on resistance to fracture of the implant-abutment complex as suggested by previous studies that showed a better performance of external hexagon designs (44). Similar results were obtained using static tests, before and after implantoplasty (IP), while comparing external, internal and conical connection designs (45).

A systematic review published by Papaspyridakos et al. (46) reported an incidence of mechanical complications ranging from 16.3% to 53.4%, after a 5-year analysis. Abutment screw fracture seems to be a common finding, with a 5 and 10-year rate of

9.3% and 18.5%, respectively. On the other hand, the average implant fracture rate has been reported to be much lower, ranging from 0.6% to 6% (46–51). However, the latter has important clinical repercussions since it usually requires the removal of both the implant and the prosthesis. Implant design and fabrication, non-passive fit of the prosthetic components and biomechanical overload are responsible for most fractures (52). Excessive occlusal forces, incorrect implant location, metal fatigue and bone resorption around the implant have also been described as critical variables for this complication (53). Specific patient-associated conditions, such as bruxism, have also been associated with the risk of developing mechanical complications, even though the available data is still scarce (54).

Implant diameter is also a variable that must be taken into consideration regarding this problematic. Considering the average bite forces, narrow implants (i.e. with a diameter ≤3.5mm) can be more prone to fracture in the molar area (53). Nevertheless, the use of regular- or wide-platform implants (i.e. with a diameter of >3.5mm) does not guarantee the absence of mechanical complications, since forces will most likely be re-directed towards less resistant components or to the bone (55–57).

Figure 1, **2** and **3** show different types of implant fractures.

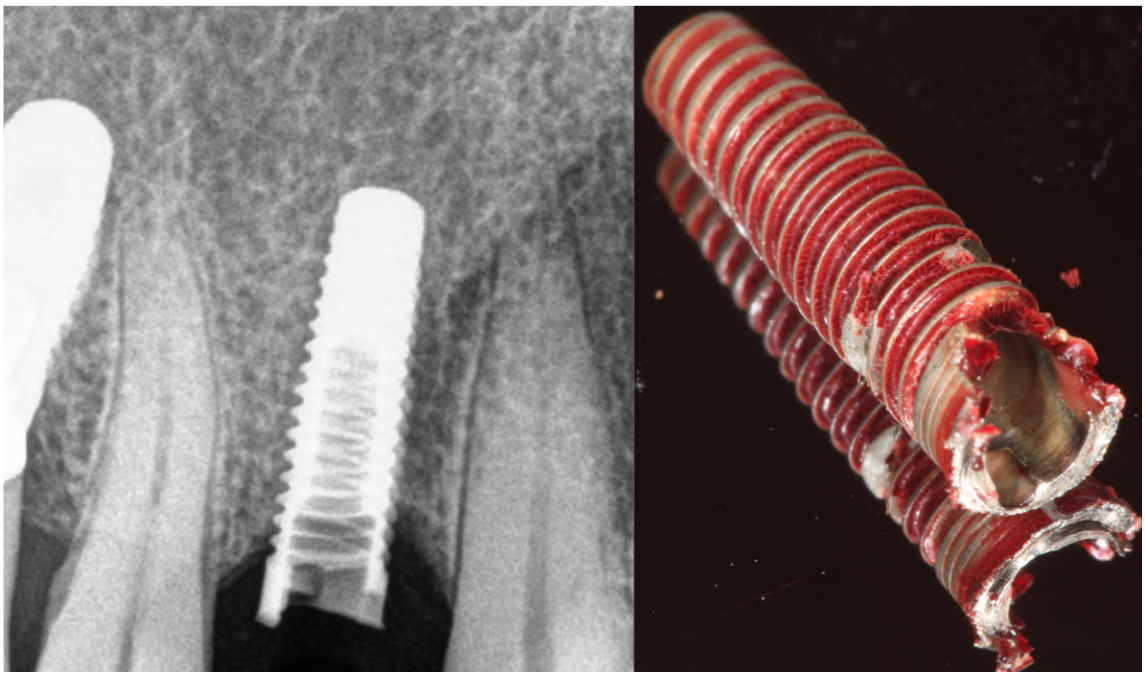

Figure 1 *Radiographic and clinical aspect of a dental implant with a platform fracture. Bone loss up to the vertical level of the fracture is clear in the radiograph. Original picture.*

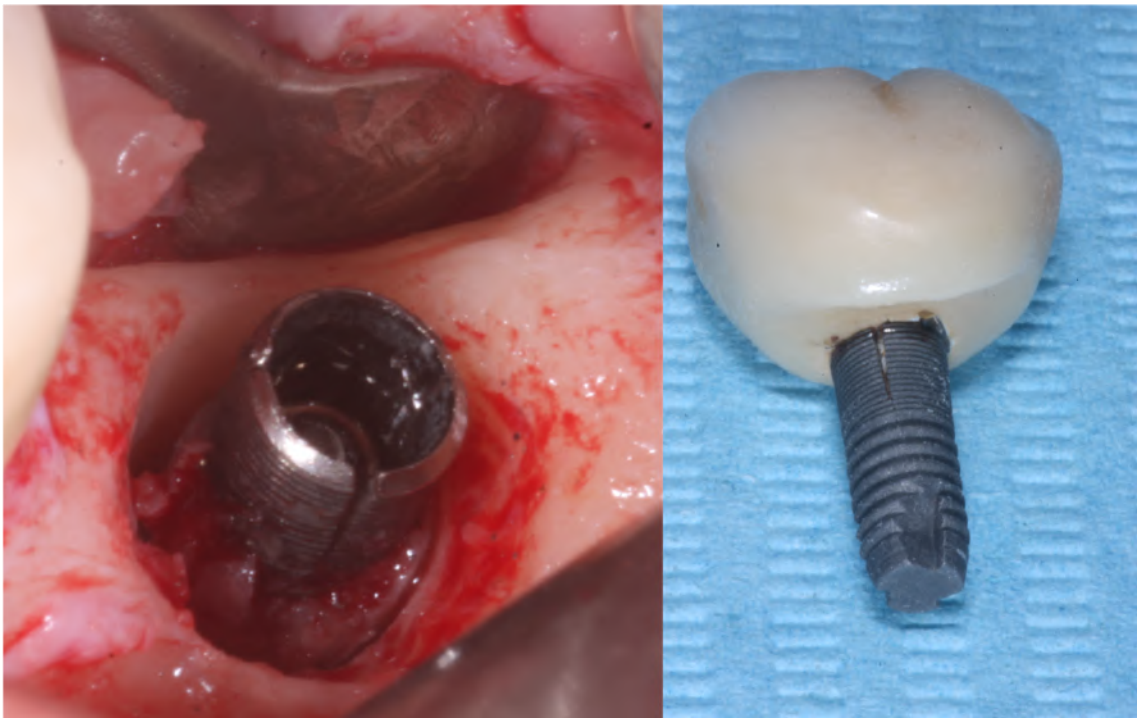

Figure 2 *Clinical view of a vertical fracture of a dental implant with circumferential peri-implant bone defect. Picture gently provided by Prof. Dr. Tiago Borges.*

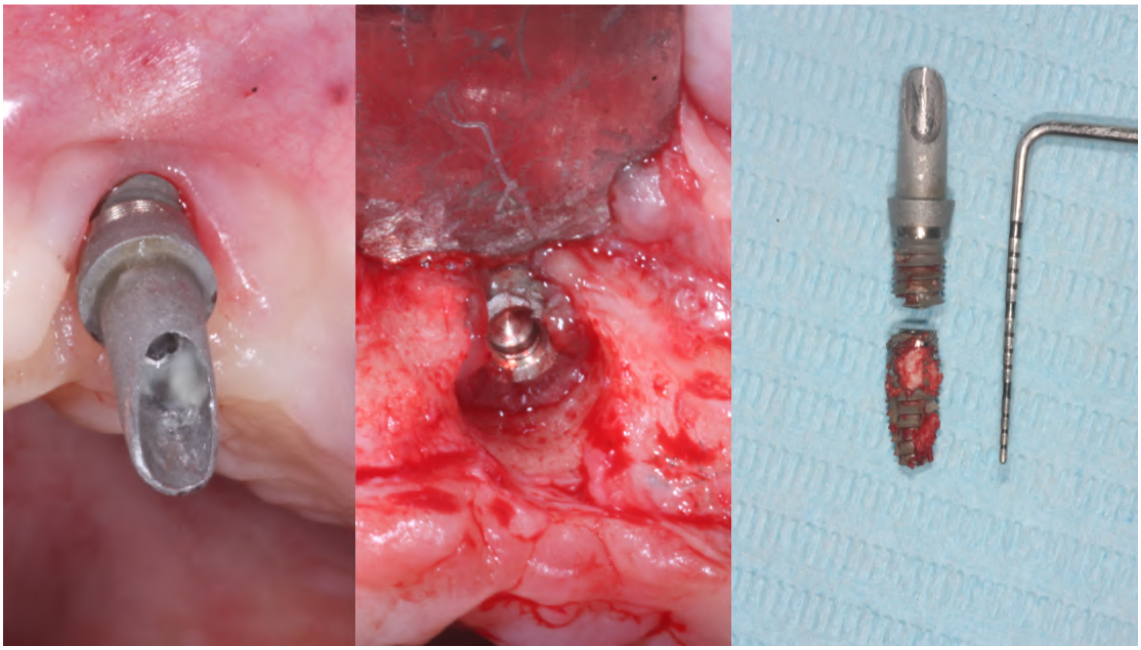

Figure 3 *Clinical view of a horizontal body fracture of a dental implant. Picture gently provided by Prof. Dr. Tiago Borges.*

Prosthetic and technical complications

Understandably, fixed prosthetic designs on osseo-integrated implants have been associated with more mechanical complications than removable ones as the tensions are distributed to the entire implant-abutment-screw-prosthesis complex (58,59). Prosthetic material wear and fracture are particularly common in full-arch metal-acrylic fixed prosthesis, but ceramic chipping is also a common reported issue both in metal or zirconia-base frameworks (60). The complete fracture of the framework is a rare but important complication that usually requires the fabrication of a new prosthesis. **Figure 4** shows a fracture of the framework of a full-arch monolithic zirconia.

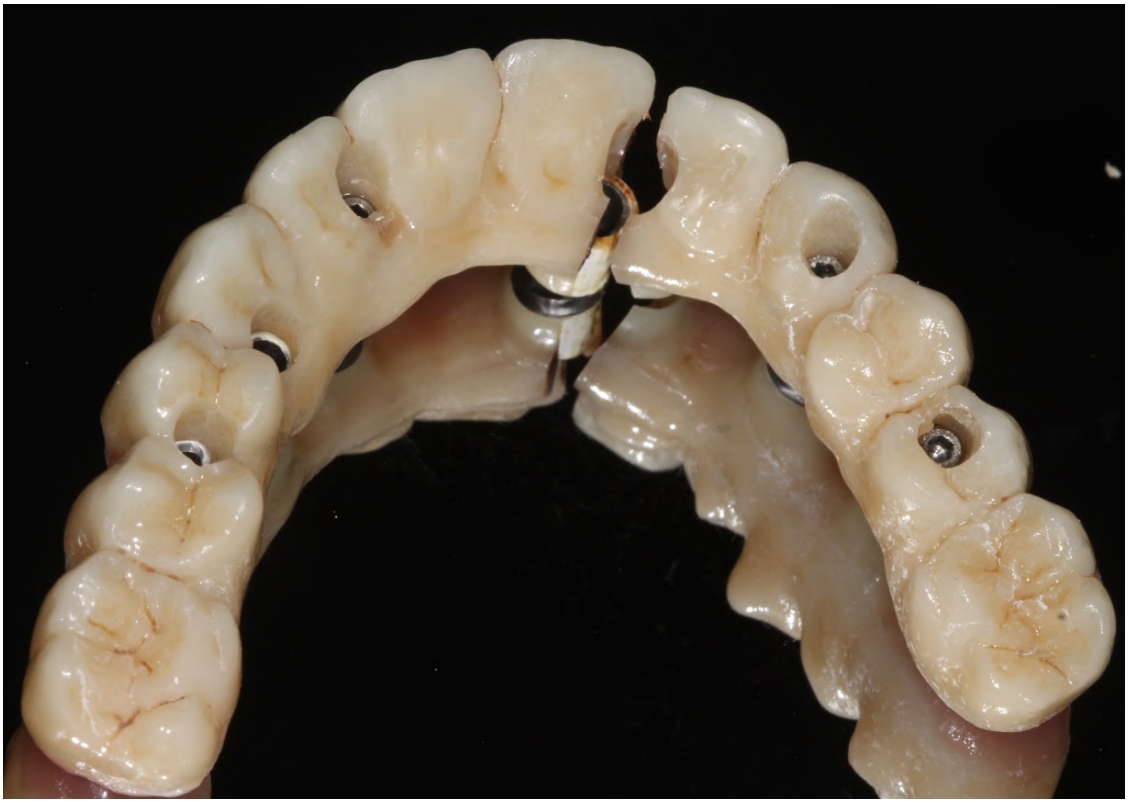

Figure 4 *Framework fracture of monolithic zirconia full-arch prosthesis. Original picture.*

The use of straight or angulated intermediate abutments has been advocated to enhance the parallelism of the implants and the passivity of the framework, while redirecting occlusal stress forces to the intermediate abutment screw, therefore protecting the implant (61).

Biological complications

Concept of osseointegration failure

To be able to define failure, first we must define success. When it comes to osseointegration, several authors have provided their criteria. Zarb and Albrektsson (62), considered that osseointegration must be evaluated from a clinical point of view, defining it as a process in which a clinically asymptomatic rigid fixation is achieved and

maintained in bone during functional loading. Function (ability to chew), tissue physiology (presence and maintenance of osseointegration, absence of pain and other pathological conditions), and user satisfaction (aesthetics and absence of discomfort) have been proposed as key features when considering implant success. Papaspyridakos et al.(63) reported that success is determined by implant, soft tissue, prosthetic and patient satisfaction outcomes. Mobility, pain, radiolucency, peri-implant BL, suppuration, bleeding, technical complications, function, aesthetics, discomfort, appearance and ability to chew and taste are among these variables (63). If these criteria are not fully assessed, one can only talk about implant *survival* and not *success*. Albrektsson et al. (64) have recently updated this concept, claiming that osseointegration is a foreign body reaction and that a balanced state of chronic inflammation characterizes it. Healthy implants should not have signs of inflammation or bleeding on probing (BOP) (65).

The loss of osseointegration can be clinically and radiographically detected in the majority of cases. Indeed, implant mobility or the presence of radiolucencies are strongly associated with failures. These signs reflect the replacement of bone by a fibrous connective tissue which is unable to support an implant in function. PI might also lead to late-onset osseointegration failure, due to the progressive BL. In these situations, some treatment modalities can be useful when initial symptoms or signs are present (15).

Peri-implant mucositis

Definition

This disease can be defined as an inflammatory condition of the soft tissues surrounding an endosseous implant without loss of surrounding peri-implant bone (66).

Etiology

Using an experimental gingivitis model described by Loe et al. (67), Pontoriero et al. (68) showed that gingival indexes and probing depth increase when biofilm is not controlled. Berglundh et al. (69) using an animal model, claimed that the inflammatory infiltrate due to bacterial accumulation was similar in natural teeth and implants. Hence, the initial host response might be similar for both gingiva and peri-implant mucosa.

Prevalence

Zitzmann and Berglundh (70) have made a systematic review of cross-sectional and longitudinal studies with implants that had at least 5 years of function. These authors reported that peri-implant mucositis occurs in approximately 80% of the subjects and in 50% of the implants placed. Mir-Mari et al. (71) reported that peri-implant mucositis affected 21.6% of the implants and 38.8% of patients in a cross-sectional study that involved 245 patients with 1 to 18 years of follow-up. Similar findings were reported by Renvert et al. (72) after a 21 to 26 year follow-up of 86 patients with an average of 4 implants. In this last sample, 54.7% of the subjects showed clinical signs of peri-implant mucositis.

Diagnostic criteria

The inflammation of the peri-implant mucosa without progressive peri-implant BL is a key factor for the diagnosis. Clinically, a redness of the peri-implant mucosa, local swelling and BOP can be observed (66). **Figure 5** shows the clinical and radiographic appearance of a peri-implant mucositis.

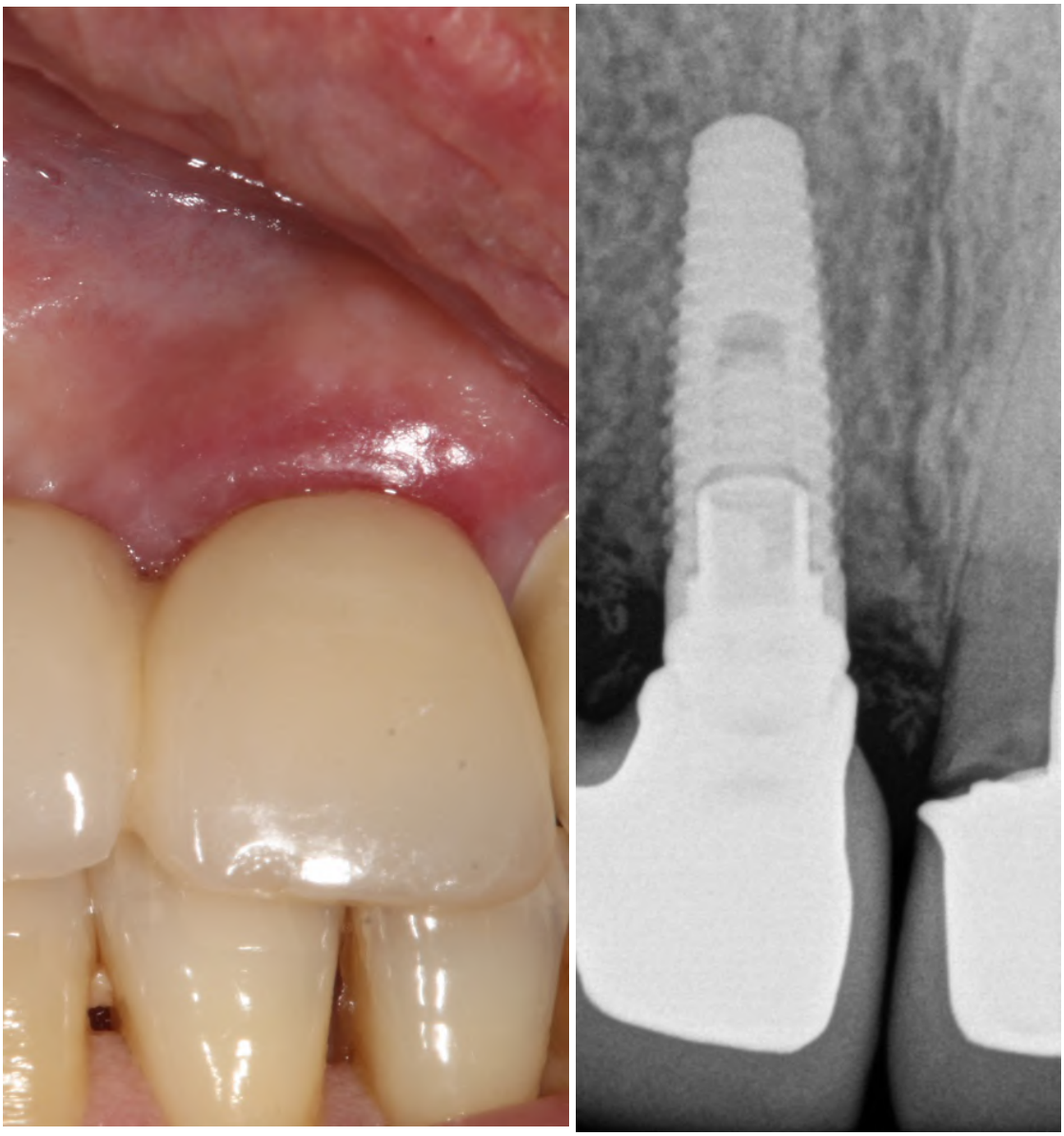

Figure 5 *Clinical and radiographic appearance of peri-implant mucositis. Original picture.*

Prevention and risk factors

Deficient oral hygiene habits (73), inconsistent supportive implant therapy(74), smoking (75), radiation therapy (75) and diabetes mellitus (73) have been reported to be risk factors for peri-implant mucositis. Other variables such as dental implant surface and material, prosthesis design and the amount of keratinized peri-implant mucosa have also been suggested to play a role in the onset of this pathology (66).

Treatment and prognosis

Peri-implant mucositis usually precedes PI and a continuum from healthy peri-implant mucosa to peri-implant mucositis and PI seems to exist (76). On the other hand, peri-implant mucositis can be present for a long time without provoking BL. It is important to stress that this entity is reversible if all initiating and risk factors are controlled (66,77).

Peri-implantitis

Definition

PI is defined as a pathological condition characterized by inflammation of the peri-implant mucosa and progressive loss of supporting bone (78).

Etiology

Many factors have been associated to the etiopathogenesis of this condition. Most authors agree that bacteria play an important role in this condition. Gram-negative rods such as *Prevotella intermedia, Treponema denticola, Tanarella forsythia, Aggregatibacter actinomycetemcomitans* and *Porphyromonas gingivalis* along with fusiform bacteria, motile or curved rods, as well as spirochetes have been associated with PI. *Peptostreptococcus spp.* and *Staphylococcus spp.* are also of significance for this complication (79–81). The development of a biofilm attached to the implant surface seems to be critical in the development of peri-implant diseases and could be responsible for altering the implant surfaces (82–84) as **Figures 6** and **7** demonstrate.

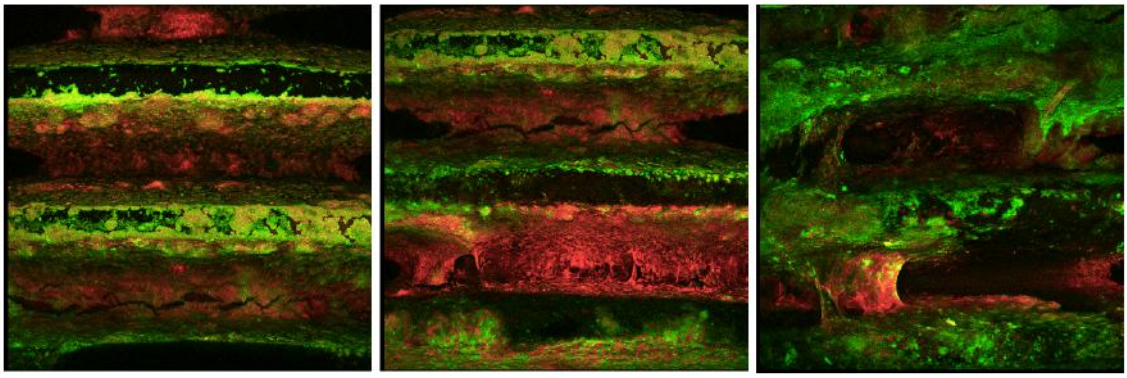

Figure 6 *Confocal fluorescence microscopy demonstration of supra-gingival biofilm. Picture gently provided by Dra. Berta Cortés Acha (84).*

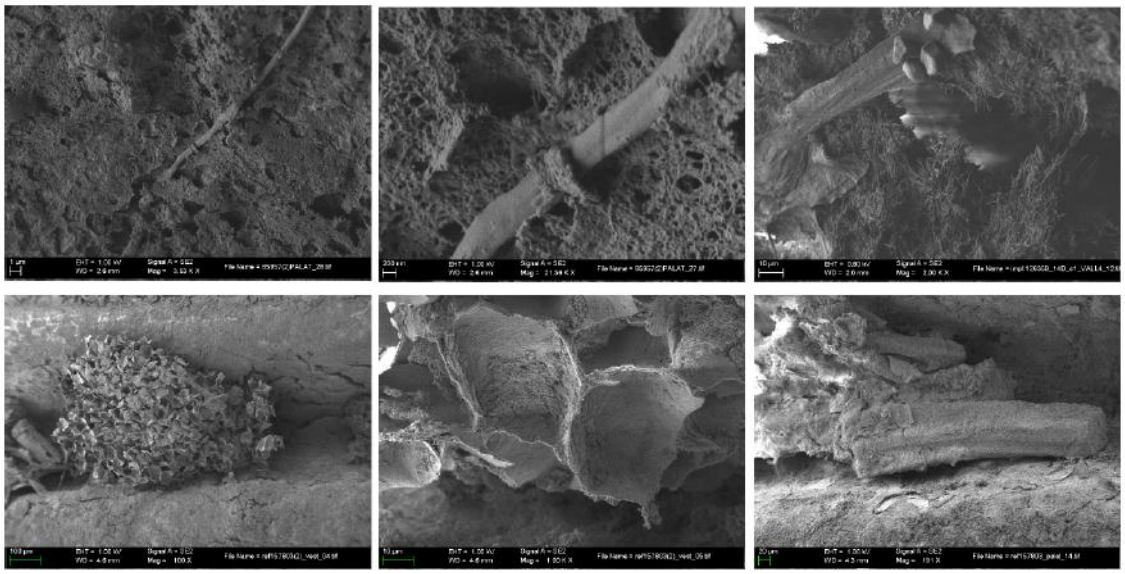

Figure 7 *Structures with atypical morphology embedded in abutment biofilm under SEM. Picture gently provided by Dra. Berta Cortés Acha (84).*

Different mechanisms are involved: direct invasion and destruction, release of enzymes and bone resorptive factors, evasion of the host defences and indirect host mediated inflammatory reaction (85,86).

Lindhe et al. (87), using an animal model on Beagle dogs, induced PI by creating bacterial accumulation conditions. Using a similar methodology on monkeys, Lang et al. (88) induced both periodontitis and PI. Increase of plaque and gingival indexes, pocket depth and loss of insertion were recorded in both studies. The local inflammatory response and

the misbalance in the host-pathogen interaction might lead to tissue destruction that usually characterizes PI (81).

On the other hand, the relation between microbiome and biomaterial might lead to titanium or zirconia degradation, suggesting that peri-implant biofilm changes might be paramount for PI development (89).

Prevalence

Zitzmann and Berglundh (70) reported that PI affects 28-56% of the subjects and 12-43% of the implants. Renvert et al. (72) also found a high prevalence of PI since 22.1% of the subjects showed clinical signs of the disease after 21 to 26 years of follow-up.

Mir-Mari et al. (71) reported, in a cross-sectional study made in a private practice, that 9.1% of the implants and 16.3% of the patients develop PI. More recently, Rakic et al. reported that PI can affect 18.5% of the patients and 12.8% of the implants (90).

PI seems to progress in a non-linear pattern usually starting within 3 years of function. Indeed, evidence suggests that 2/3 of implants will present BL of more than 0.5mm after 3 years in function (91).

Diagnostic criteria

Clinical signs of inflammation, BOP and/or suppuration, increased probing depth and/or recession of the gingival margin in addition to successive radiographic evidence of bone loss are the landmarks for the diagnosis of PI (92). **Table 1** summarizes the main diagnostic criteria for peri-implant diseases.

Table 1 *Summary of diagnostic variables for peri-implant health, peri-implant mucositis and peri-implantitis based on the outcomes of the 2017 World Workshop on the Classification of Periodontal and Peri-implant Diseases and Conditions (92)*

	Peri-implant health	**Peri-implant mucositis**	**Peri-implantitis**
BOP	N	Y	Y
Suppuration	N	Y/N	Y/N
Erythema	N	Y/N	Y/N
Swelling	N	Y/N	Y/N
Progressive loss of bone	N*	N	Y

N= Absent; Y= Present; Y/N= May or may not be present; BOP = bleeding on probing

* Note that peri-implant health is possible around implants with reduced bone support

BL over 2 mm, BOP and probing depths of more than 5mm have previously been proposed as clinical landmarks for diagnosis (37). It is also important to take into consideration that periapical x-rays usually underestimates the real BL, as has been shown by García-García et al. (93).

BOP has been used for clinical assessment of periodontal disease with a reported sensitivity of 90.9% and specificity of 77.3% for gingival health (94). On the other hand, BOP seems to be less accurate for the diagnosis of PI. A recent systematic review and meta-analysis claimed that the sensitivity of this parameter was of 24.1% (implant-based analysis) and of 33.8% (patient-based analysis), thus suggesting that BOP might generate false positives when diagnosing PI (95). Nonetheless, gentle probing is still considered a valuable resource for assessing peri-implant diseases. Indeed, the 2017 World Workshop on the Classification of Periodontal and Peri-implant Diseases and Conditions (92) states that changes in probing depth and specially BOP are key variables for the diagnosis of peri-implant diseases. Still, it is important to consider that probing depends on a variety

of factors such as the applied force, the profile and shape of the abutments, implants and prosthesis (96,97).

Figure 8 shows radiographic and clinical aspects of an advanced peri-implantitis that resulted in implant loss.

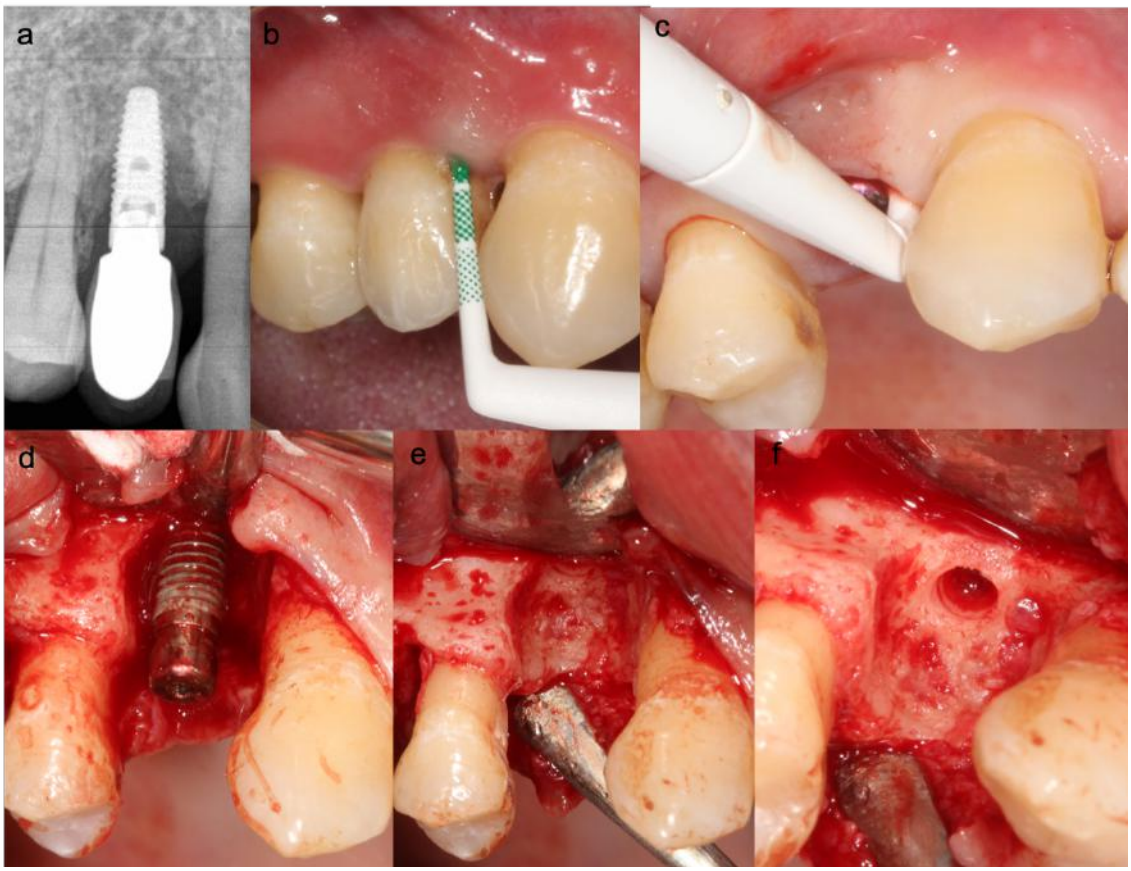

Figure 8 *Advanced peri-implantitis.* ***a)*** *Radiographic appearance showing BL;* ***b,c)*** *Increased probing depth with BOP and suppuration;* ***d)*** *Implant exposure after removal of granulation tissue;* ***e,f)*** *Circumferential bone defect resulting from peri-implantitis, after implant removal. Original picture.*

Prevention and risk factors

Poor oral hygiene, history of periodontitis and lack of regular support therapy after implant placement are considered to be risk factors for PI (78). Other factors like smoking, genetic traits, implant surface, alcohol consumption, lack of keratinized mucosa and some systemic diseases also seem to be related with the onset and progression of PI, even though further research is needed to confirm these associations (15,81,85,98,99).

Smeets et al. (100) recommended frequent peri-implant support therapy sessions in smoking patients with poor oral hygiene, with previous history of peri-implant mucositis, PI or implant loss and with other systemic risk factors . Recommendations on frequency of support recalls are summarized in **Table 2**.

Table 2 *Recommendations on frequency of support recalls. Adapted from Smeets et al. (100).*

Recommended sessions/year	1	2	≥3
Oral hygiene	Good	Average	Bad
Smoking habits	No	Ex-smoker	Yes
History of peri-implant mucositis / PI	No	No	Yes
Other risk factors	No	No	Other systemic disease, history of implant loss

Treatment and prognosis

Since bacterial colonization and inflammation seem to play a major role in the etiology of PI, treatments should be aimed at disrupting the biofilm, decontaminating the implant, reducing the peri-implant pockets and improving the access to oral hygiene in order to stop the development and progression of the condition (80).

Access to infected sites can be difficult due to the prosthesis, implant design or defect configuration. As so, open-flap treatments with or without adjunctive therapy seem the to be the most adequate approach, while non-surgical strategies seem to be less effective in controlling PI (82). For implant surface detoxification, several approaches have been

tested: air-powder abrasion, ultrasonic and manual debridement (using plastic, carbon stainless steel, graphite and titanium curettes), implantoplasty (IP), laser therapy, among others (101). Chemical agents seem to improve the results of the mechanical debridement. Agents such as citric acid, hydrogen peroxide, cetylpyridinium chloride, tetracyclines, EDTA (ethylenediaminetetraacetic acid) and chlorhexidine appear to improve the treatment outcomes (102). However, Carcuac et al. (103) reported that the use of chlorhexidine provided no additional overall effect and that systemic antibiotics only seemed to have a mild effect when rough surface implants were involved. These authors also reported that the treatment success was higher in machined surface implants in comparison with fixtures with a modified surface (79% *vs.* 34%).

Resective, regenerative and combined surgical approaches have been described in the literature. The selection criteria for the most suitable technique should consider several factors like the defect morphology and shape, the presence or absence of keratinized mucosa and the location of the implant. Resective approaches seem to be more suitable to treat suprabony defects, one-wall infra-bony defects or buccal bone dehiscences in non-aesthetic zones. This option aims at reducing the probing depth and obtaining a more favourable soft-tissue anatomy to facilitate biofilm removal. The surgical technique consists of raising a full-thickness flap, removal of the granulation tissue, detoxification of the exposed implant surface, correction of the anatomical architecture of the bone, modification of the roughness of implant surface and establishment of an efficient plaque control regimen (104,105).

Clinical evolution of a PI full-arch case treated with resective approach is depicted in **Figures 9** to **13**.

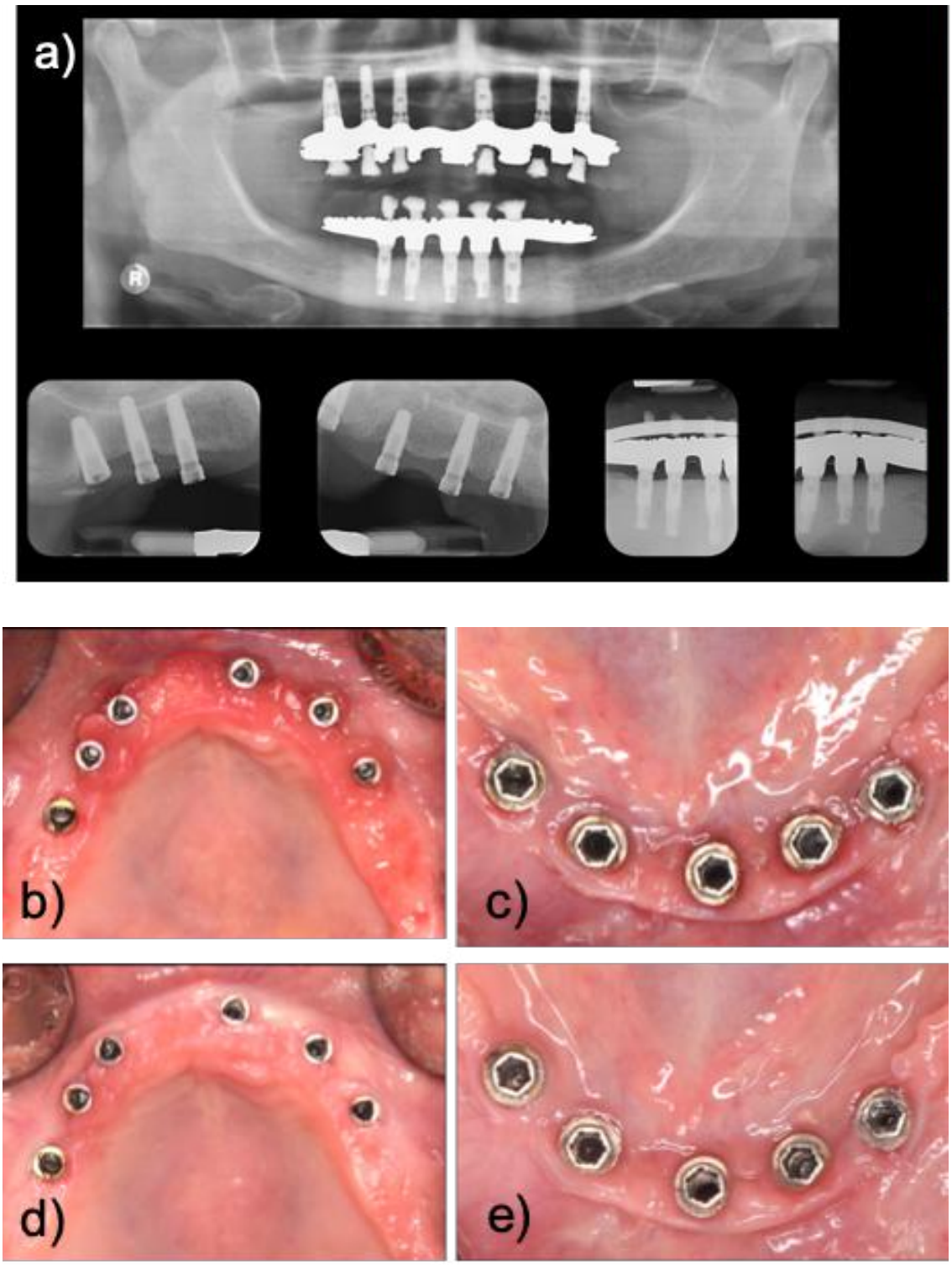

Figure 9 *Full-arch peri-implantits case.* ***a)*** *Panoramic and apical x-rays showing bone loss in upper implants;* ***b,c)*** *Initial clinical appearance of soft tissues, upper and lower;* ***d, e)*** *Soft tissue improvement after non-surgical treatment, upper and lower. Case treated in the Implant Maintenance Unit of the Master degree program in Oral Surgery and Implantology of the Universitat de Barcelona.*

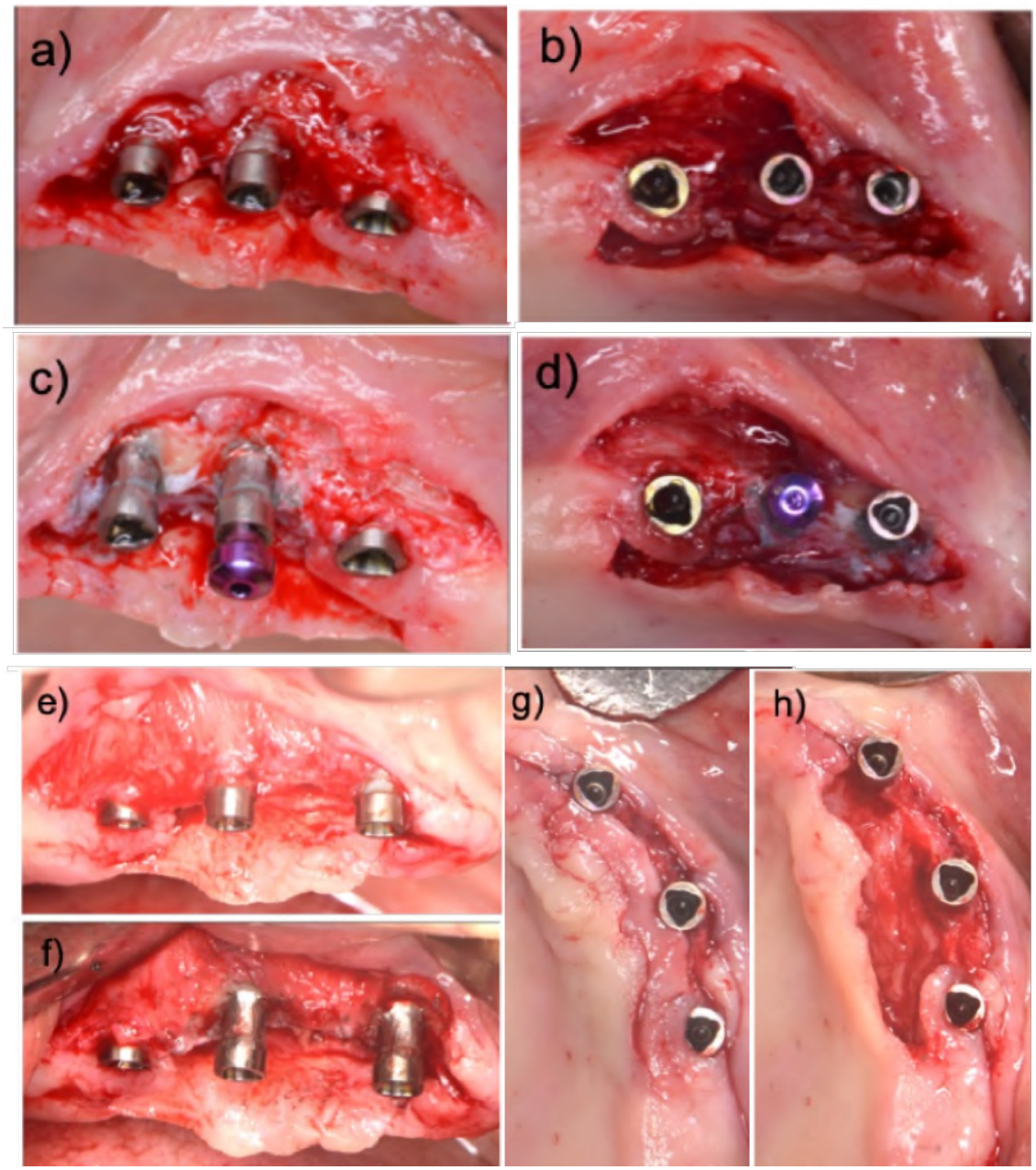

Figure 10 *Full-arch PI case.* ***a,b)*** *Upper right side upon flap opening;* ***c,d)*** *Upper right side after bone remodelling and implantoplasty;* ***e,g)*** *Upper left side upon flap opening;* ***f,h)*** *Upper left side after bone remodelling and implantoplasty. Case treated in the Implant Maintenance Unit of the Master degree program in Oral Surgery and Implantology of the Universitat de Barcelona.*

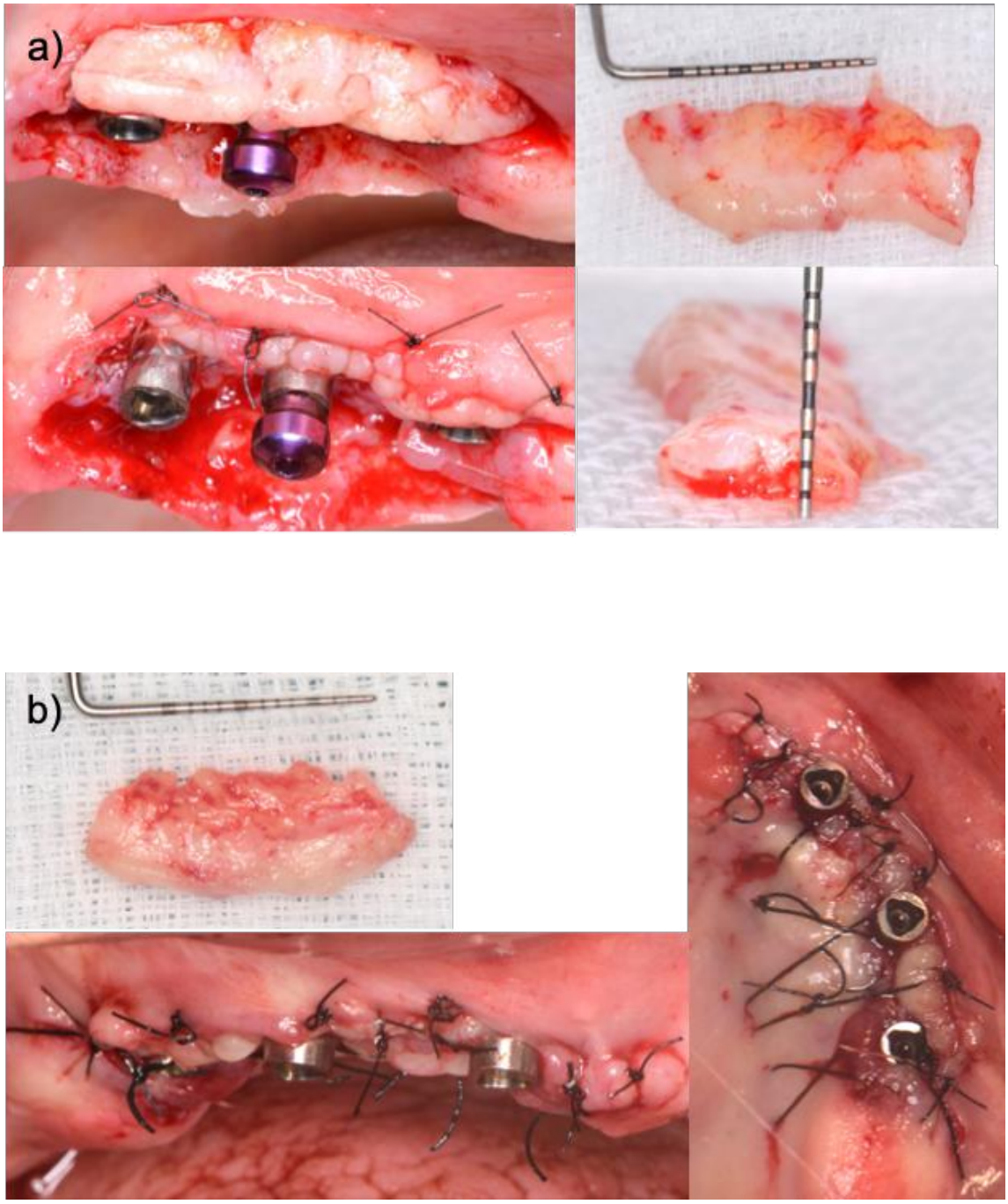

Figure 11 *Full-arch PI case.* ***a)*** *Detail of connective tissue graft on the upper right side after resective procedure;* ***b)*** *Detail of connective tissue graft on the upper left side after resective procedure. Case treated in the Implant Maintenance Unit of the Master degree program in Oral Surgery and Implantology of the Universitat de Barcelona.*

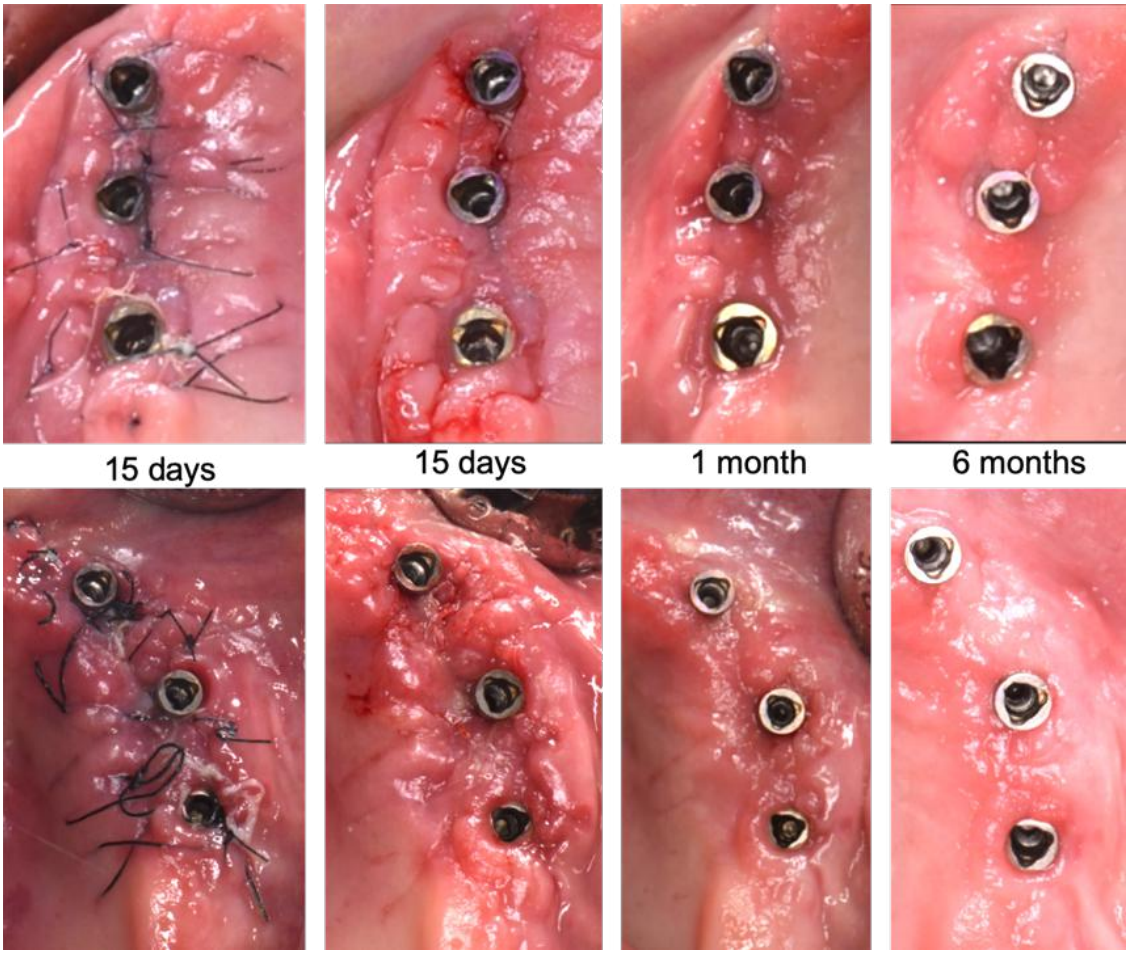

Figure 12 *Full-arch PI case. Soft tissue evolution at suture removal (15 days), 1 month and 6 months follow-up appointment. Case treated in the Implant Maintenance Unit of the Master degree program in Oral Surgery and Implantology of the Universitat de Barcelona.*

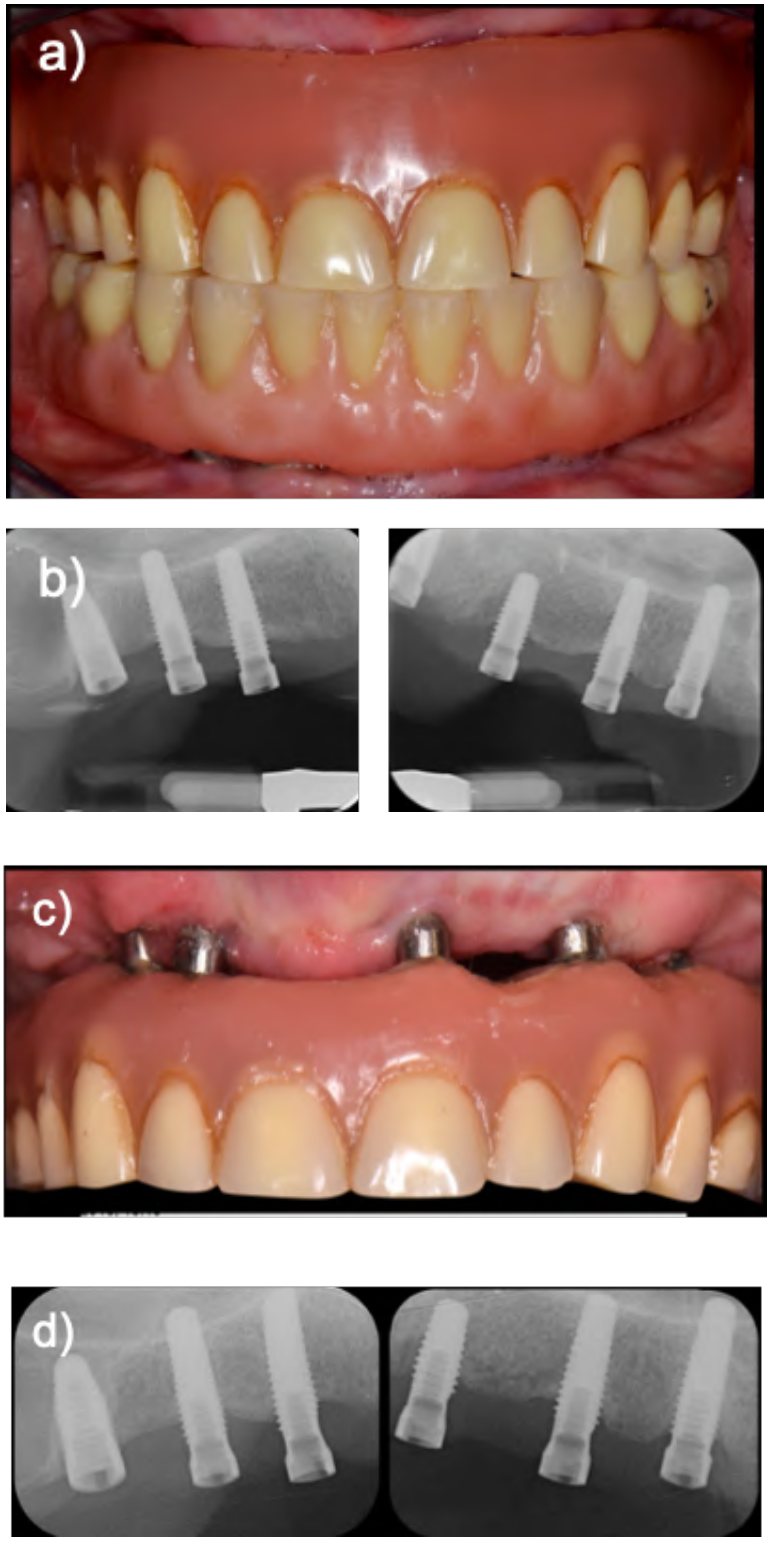

Figure 13 *Initial and 15-month follow-up of full-arch PI case.* ***a)*** *Initial poor prosthesis design;* ***b)*** *Initial apical x-rays showing bone loss;* ***c)*** *15 months after resective surgery with improved prosthetic design and soft tissue healing;* ***d)*** *Apical x-rays 15 months after resective surgery. Case treated in the Implant Maintenance Unit of the Master degree program in Oral Surgery and Implantology of the Universitat de Barcelona.*

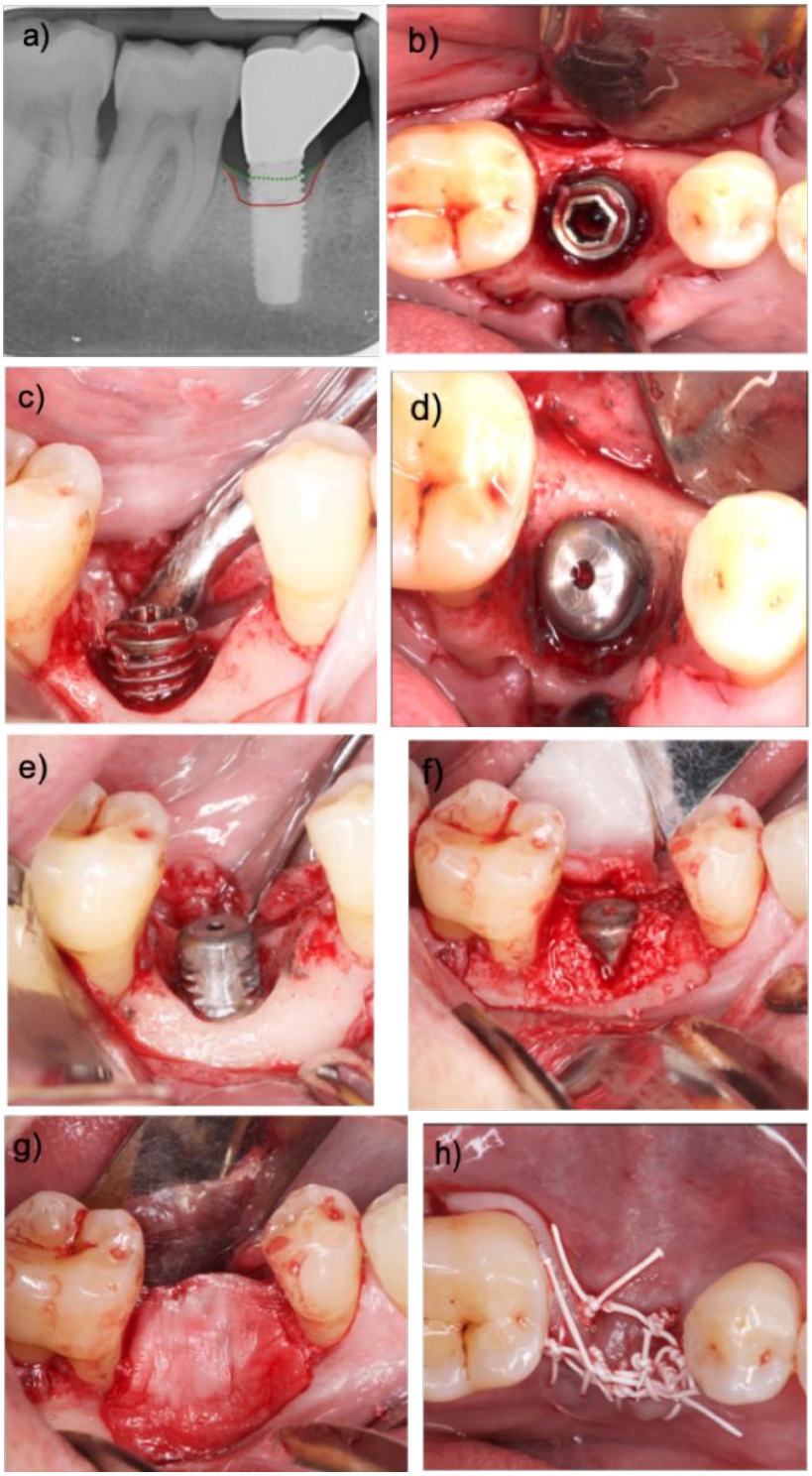

Figure 14 *Combined approach in a single implant peri-implantitis case.* ***a)*** *apical x-ray demonstrating crater-like bone defect;* ***b, c)*** *occlusal and buccal view after soft tissue debridement;* ***d, e)*** *occlusal and buccal view after bone remodelling and implantoplasty;* ***f)*** *xenograft application;* ***g)*** *collagen membrane cover;* ***h)*** *PTFE suture. Case treated in the Implant Maintenance Unit of the Master degree program in Oral Surgery and Implantology of the Universitat de Barcelona.*

On the other hand, a regenerative approach that uses grafting materials and membranes is particularly indicated for crater-like self-containing bone defects (105). A combined resective and regenerative approach is showed in **Figure 14**.

Explantation of the implant(s) affected by severe PI is a last resort option(106) and a technique using an implant retriever for this procedure, is depicted in **Figure 15**.

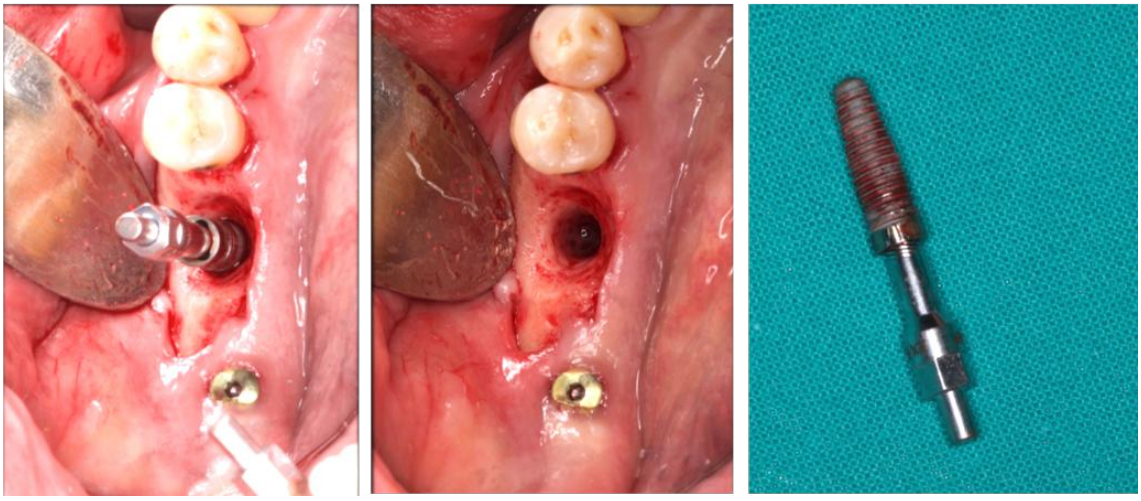

Figure 15 *Explantation of implant affected by severe peri-implantitis using an implant retriever. Case treated in the Implant Maintenance Unit of the Master degree program in Oral Surgery and Implantology of the Universitat de Barcelona.*

There are no standardized, universally accepted treatment protocols for the treatment of peri-implant diseases, even though most authors state that non-surgical therapies are only effective for peri-implant mucositis and have a limited effect on PI cases (82). Also, it is unclear which is the most effective surface detoxification protocol. Thus, further randomized controlled clinical trials with long-term results are required to identify the most effective treatments (102,107). Also, it is important to stress that all patients with PI should initially undergo a non-surgical treatment to control the risk factors, to improve access to oral hygiene and to reduce the soft tissue inflammation before surgery.

Figure 16 summarizes clinical approach options for the maintenance and intervention on dental implants.

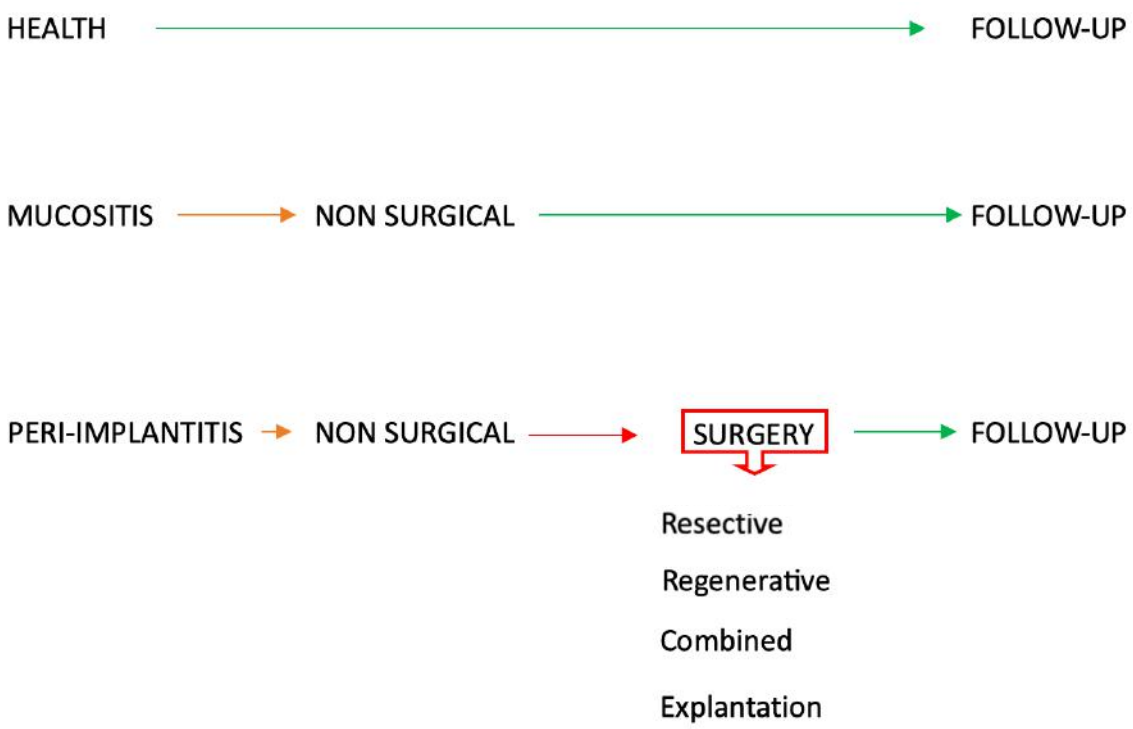

Figure 16 *Maintenance and intervention protocols for dental implants. Figure gently provided by Dr. Javier Mir-Mari.*

6. Implantoplasty

Implantoplasty is a procedure that consists of polishing the rough implant surfaces that are outside of the bony envelope thus making them less prone to biofilm accumulation. **Figure 17** shows the macroscopic change after this procedure.

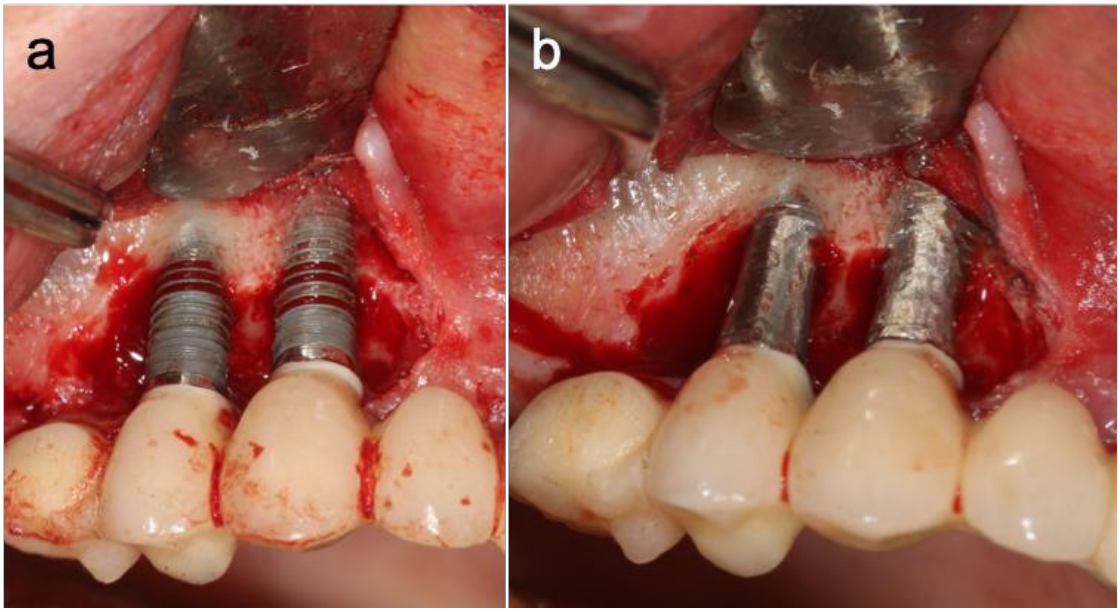

***Figure 17** Before **(a)** and after**(b)** IP procedure in a severe PI case. Original picture.*

This technique seems to stop marginal BL effectively and leads to a significant decrease of BOP and of the pocket probing depths (102,104,108–111). A clear correlation has been reported between the implant surface roughness and the rate of bacterial colonization, both supra- and sub-gingivally (34,112). An increased surface roughness may also lead to an incomplete biofilm removal and might expose a larger area for bacterial adhesion (85). The main biological rationale that supports IP is that a polished surface hampers bacterial adhesion, facilitates its removal and prevent future biofilm regrowth. Furthermore, with this technique surgeons can detoxify implant surfaces. Indeed, lower levels of inflammatory mediators have been found after IP procedures (113).

Several reports seem to indicate that IP is an effective procedure associated with a high implant survival rate (108,114–116). On the other hand, a recent retrospective study based on 41 patients with 68 implants affected by PI, suggested that IP may not be decisive to increase implant survival rates and that the amount of marginal BL seems to be the main prognostic factor (117). **Figure 18** depicts the evolution after 2 years of severe case of PI on a 75-year-old female patient treated with IP.

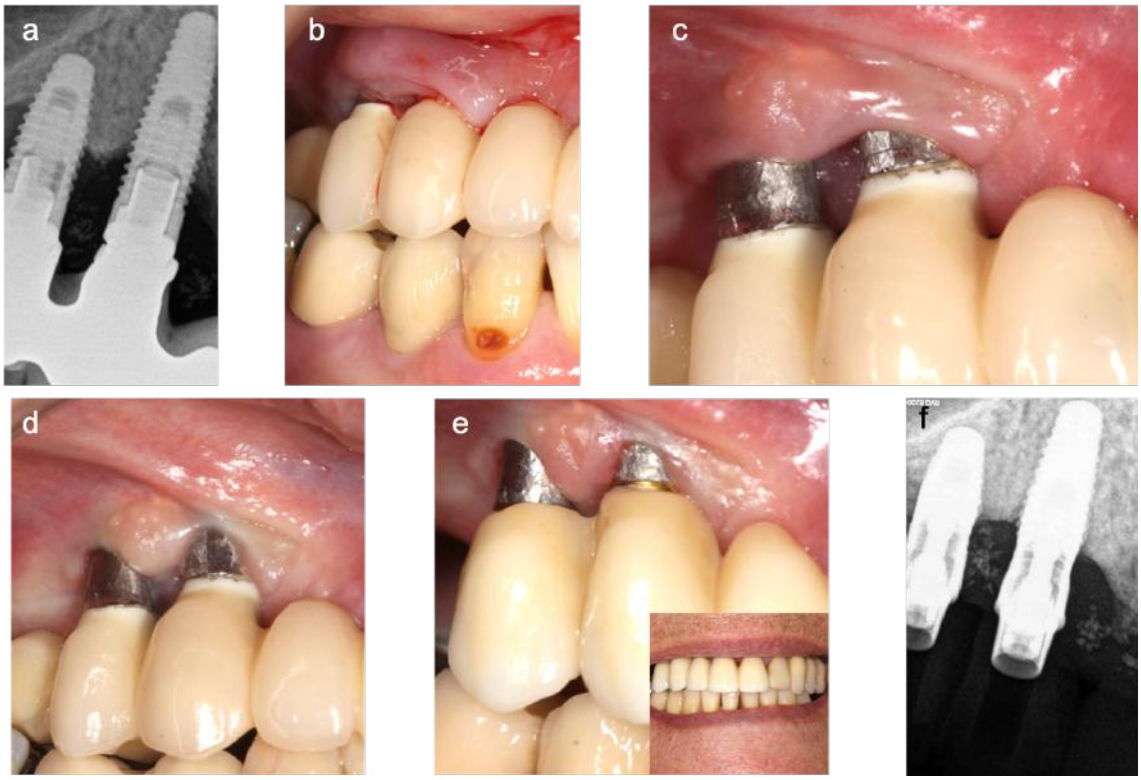

Figure 18 a) *Initial periapical x-ray;* ***b)*** *Preoperative aspect of the soft tissues with pain, bleeding and suppuration;* ***c)*** *1.5 months after a resective surgical approach with IP;* ***d)*** *6 months after the procedure;* ***e)*** *2 years follow-up with soft tissue stability and no aesthetic impairment, signs or symptoms;* ***f)*** *periapical x-ray after 2 years. Original picture.*

Implantoplasty technique

This technique usually requires the combination of high-speed surgical hand-pieces with diamond or carbide burs to remove the exposed threads and the surface of the implant. Afterwards, silicon polishers are used to further smoothen and polish the surface. Several combinations of burs have been described in the literature (104,108,118–120). The intermediate use of an Arkansas bur between these two steps has also been previously proposed (121).

IP is a time-consuming procedure with a mean duration that ranges between 12 and 21 minutes *per* implant in an *in vitro* setting (122).

Concerns about implantoplasty

Several concerns have been raised with IP procedures: perforation of the implant body, damage to the implant-abutment connection, platform deformation, loosening of the prosthetic screw, implant fracture, thermal damage to the surrounding bone, mucosal staining and late inflammatory reactions due to titanium debris. However, there is very limited data or clinical evidence that IP is associated with any remarkable mechanical or biological complications on the short or medium-term (123).

Thermal damage

Thermal damage occurs when temperatures exceed 47°C for more than one minute since these can cause irreversible bone cell damage and might lead to bone resorption and delayed healing (124). Heat shocks of 42°C can also induce transient changes to osteoblasts (125). Sharon et al. (126) studied thermal changes that occur during IP procedures and concluded that, under proper water-spray irrigation, the temperature changes are not clinically significant (increase of 1.5°C). Thus, in this sense, IP seems to be a safe technique.

Release of titanium debris

IP can cause release and nearby tissue deposition of titanium debris. Titanium alloys can release ions and particles that might not be entirely bio-inert, contributing to the development and progression of peri-implant diseases (119). Concentrations of titanium particles seem to be higher at PI sites in comparison with healthy implants, suggesting a strong association between titanium particles and peri-implant disease (127–130). Titanium particles could be the result of corrosion of the implant surface, insertion of the implant into the osteotomy site, implant-abutment friction, non-surgical mechanical

debridement or IP. Corroded debris can be cytotoxic and have the potential to tattoo soft tissues(131,132). Therefore, clinicians should consider using barriers such as a rubber dam and a high volume suction devices during IP to prevent tissue contamination (133). Further research is needed on this topic to determine the possible systemic and local effects of these titanium particles.

Implant fracture after IP

When submitted to IP, dental implant resistance to fracture has been reported to decrease, although other variables seem to play major parts and should be considered in the risk assessment (120,134–136). This subject will be addressed thoroughly in the Discussion section of the present thesis.

7. Resistance to fracture assessment

Mastication involves complex movements that will originate cycles of compressive, torsional and bending forces to the dental implants (137). Static and dynamic tests are used to address maximal compression forces (F_{max}) and fatigue of the structures using single- or cyclic-loading techniques. Resistance to fracture testing of dental implants should be made according to ISO Standard 14801:2016. In short, samples are prepared simulating a 3mm exposure of the implant's coronal area using a standardized bone-like cast. Standardized load abutments are screwed to the implants at an appropriate torque. These samples are then stabilized in a Universal servo-hydraulic mechanical testing machine that applies a pre-determined compression load at a constant 30º angle from the vertical axis (**Figure 19 a,b,c,d)**. Real-time data is recorded throughout the test.

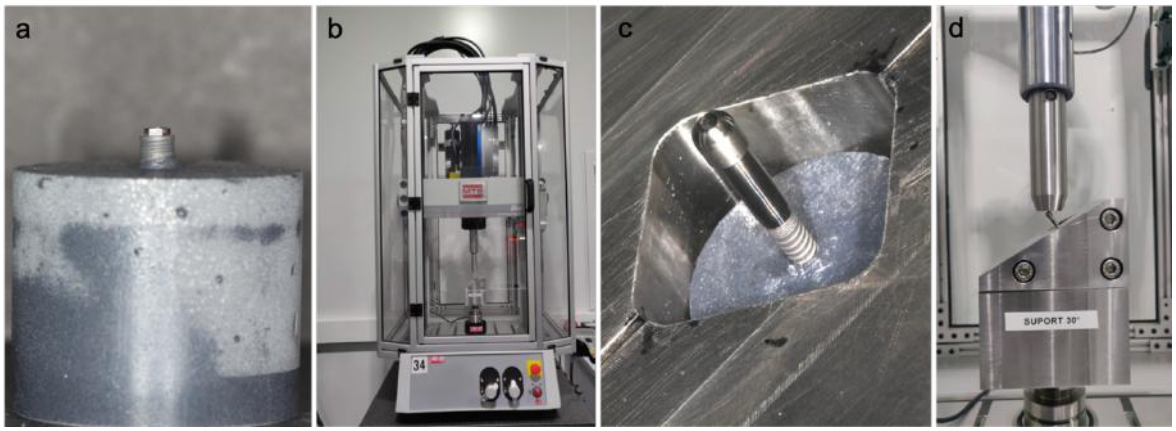

Figure 19 a) *Standardized implant sample;* ***b)*** *Universal servo-hydraulic machine (MTS Bionix 370 Load Frame, MTS®, Eden Prairie, USA);* ***c)*** *Clamping device detail and sample with loading abutment in place at 30°;* ***d)*** *Loading of the sample. Original picture.*

Results of resistance to fracture tests are affected by the contact surface area, embedment depth of the fixture, prosthetic screw length and material of the implant (138).

8. Crown-to-implant ratio and bone loss

Considering that dental implants are frequently placed in moderately or severe resorbed maxillae and mandibles, crown-to-implant ratios (CIRs) over 2 are common. Moreover, when peri-implant BL appears, the CIR increases.

Tawil et al. (139) defined anatomical and clinical CIR´s, taking into consideration the position of the fulcrum. For the anatomical ratio, the fulcrum is established at the interface of the implant shoulder and the crown/abutment system and for the clinical ratio the fulcrum is established at the most coronal bone-implant contact as demonstrated in **figure 20**.

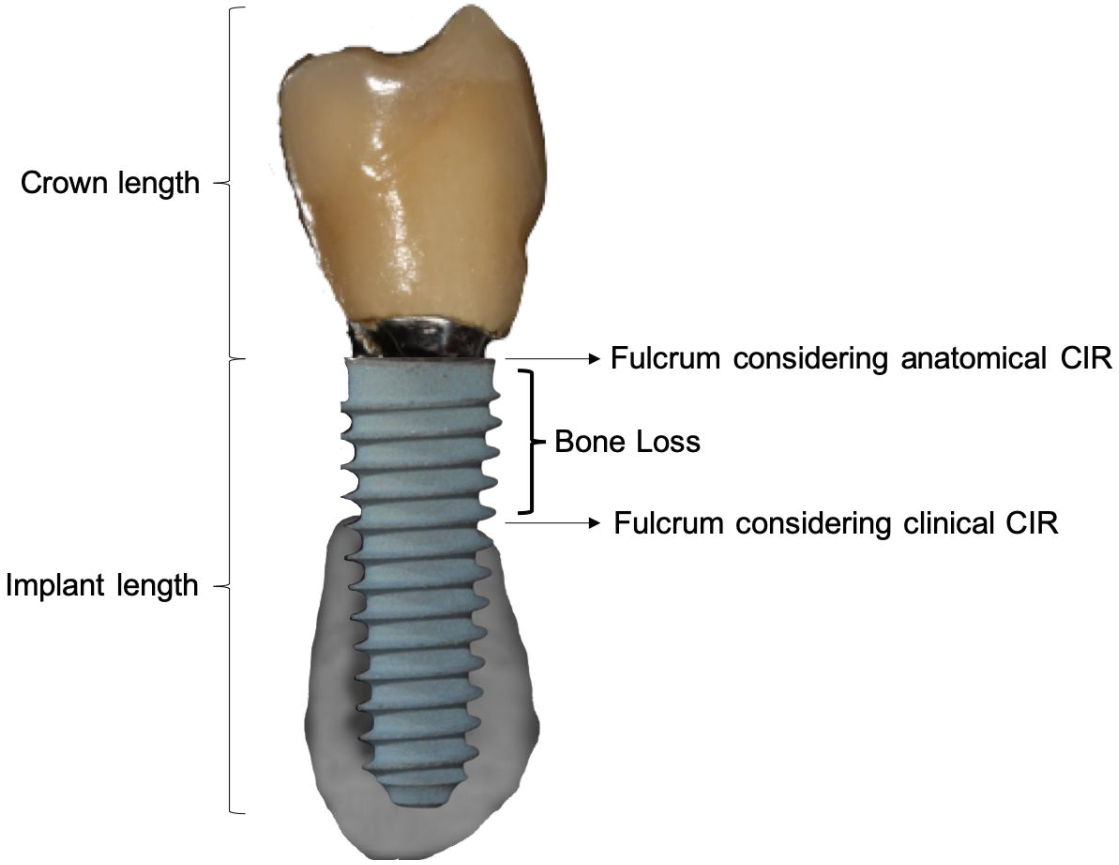

Figure 20 *Anatomical/clinical Crown-to-implant ratio and bone loss. Adapted from Ravidà A et al. (141).*

A high CIR has been associated with a detrimental effect over time in natural teeth (140). This might not be the case in dental implant rehabilitations, as several reports have shown that high CIRs do not seem to be directly related with increased marginal BL neither seem to be a biomechanical risk factor for the prosthesis (141–143). CIRs between 0.86 and 2.14 in single tooth, non-splinted implants have been analysed, and no significant relations between this variable and the occurrence of biological or technical complications were found (144). However, this review has been criticized for having important limitations and not providing reliable information for clinical decision making (145). On the other hand, other authors have reported that CIRs higher than 1:1.46 seem to be related with prosthetic failure and increased risk of abutment fracture (146). Also, higher CIR may be responsible for an slight increase of marginal BL in short dental

implants placed in the posterior mandible (147). Finally, other papers consider that CIRs over 1.7 should be avoided (148).

A study by Gherke et al. (149) aimed at evaluating the influence of the bone insertion level on the fracture strength of implants with different connection designs. These authors concluded that resistance to loading decreases significantly with the loss of bone insertion and that the connection design can change the performance and resistance of the implant-abutment system. In 2015, Gherke (150) performed a similar study to evaluate the influence of crown height ratios on the fracture strength of implants with different connections. Again, the crown height significantly affected the resistance to fracture and the connection design was also an important variable.

9. Justification

Peri-implantitis is a highly prevalent pathology in an increasingly larger population of patients undergoing dental implant-based treatments. Thus, it is likely that in the next years, an important number of patients will require PI treatments.

As previously mentioned, implantoplasty (IP) might be beneficial and effective as part of the PI treatment, since it allows an excellent detoxification of the affected implant and a reduction of the biofilm adhesion and regrowth. However, several authors have mentioned complications that might be related with this procedure. Indeed, IP has raised concerns related with the host response to the titanium debris particles and the reduction of the mechanical properties of the implants. Regarding the latter, some studies have reported the mechanical changes that occur to dental implants after being submitted to IP. However, few data are available regarding the effect of BL and CIR on the risk of implant fracture. It must be stressed that IP is usually indicated in implants with different degrees of BL, and with unfavourable CIR ratios.

Therefore, this thesis aims to clarify, using 2 *in vitro* studies, if IP significantly weakens dental implants in several clinical conditions that simulate different amounts of BL and various CIR. The results of these studies will provide useful information, since it will allow clinicians to evaluate the risk of fracture in implants with peri-implantitis that require IP.

HYPOTHESIS

Main hypotheses

- Implantoplasty increases the risk of fractures of dental implants, regardless of the degree of bone loss and of the clinical crown-to-implant ratio (CIR).
- A higher degree of bone loss leads to a reduced resistance to fracture of implants with and without implantoplasty.
- An unfavourable clinical CIR decreases the resistance to fracture of implants with and without implantoplasty.

Specific hypotheses

- Implantoplasty reduces the maximal compression forces of narrow 3.5-mm-wide platform external hexagonal connection implants, when submitted to a load at 30º from the vertical axis.
- The maximal compression forces of 3.5-mm-wide platform external hexagonal connection implants, with and without implantoplasty, with 3mm of bone loss are significantly higher in comparison with similar implants with 7.5mm of bone loss, when submitted to a load at 30º from the vertical axis.
- The maximal compression forces of 3.5-mm-wide platform external hexagonal connection implants, with and without implantoplasty, with a 3:1 clinical CIR are significantly lower in comparison with similar implants with a 2:1 CIR, when submitted to a load at 30º from the vertical axis.
- Implantoplasty significantly reduces the width of the dental implant walls.
- Most fractures of dental implants occur in the platform area, regardless of the degree of bone loss and of the clinical CIR.

OBJECTIVES

Main objectives

- To determine if implantoplasty affects the resistance to fracture of dental implants, regardless of the degree of bone loss and of the clinical crown-to-implant ratios (CIR).
- To evaluate if the degree of bone loss affects the resistance to fracture of implants with and without implantoplasty.
- To determine whether the clinical CIR influences the resistance to fracture of implants with and without implantoplasty.

Specific objectives

- To determine the maximal compression forces of narrow 3.5-mm-wide platform external hexagonal connection implants, with and without implantoplasty, when submitted to a load at 30º from the vertical axis, with different bone levels and CIRs.
- To compare the maximal compression forces of 3.5-mm-wide platform external hexagonal connection implants, with and without implantoplasty, with 3mm and 7.5mm of bone loss, when submitted to a load at 30º from the vertical axis.
- To compare the maximal compression forces of 3.5-mm-wide platform external hexagonal connection implants, with and without implantoplasty, with 3 different clinical CIRs (3:1; 2.5:1; 2:1), when submitted to a load at 30º from the vertical axis.
- To measure the reduction in the dental implant walls caused by implantoplasty.
- To determine the most common location of fractures in implants with different clinical CIRs and bone levels.

MATERIAL AND METHODS / RESULTS

Publication 1

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Effect of crown to implant ratio and implantoplasty on the fracture resistance of narrow dental implants with marginal bone loss: an in vitro study

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Abstract

Background: Peri-implantitis is a biological complication that affects soft and hard tissues around dental implants. Implantoplasty (IP) polishes the exposed implant surface, to decontaminate it and make it less prone to bacterial colonization. This study investigates whether a higher clinical crown-to-implant-ratio (CIR) reduces implant fracture resistance and whether implants are more fracture-prone after IP in the presence of 50% of bone loss.

Methods: Forty-eight narrow platform (3.5 mm) 15 mm long titanium dental implants with a rough surface and hexagonal external connection were placed in standardized bone-like resin casts leaving 7.5 mm exposed. Half were selected for IP. The IP and control groups were each divided into 3 subgroups with different clinical CIRs (2:1, 2.5:1 and 3:1). The implant wall width measurements were calculated using the software ImageJ v.1.51 through the analysis of plain x-ray examination of all the samples using standardized mounts. A fracture test was performed and scanning electron microscopy was used to evaluate maximum compression force (F_{max}) and implant fractures.

Results: IP significantly reduced the implant wall width ($P < 0.001$) in all reference points of each subgroup. F_{max} was significantly higher in the 2:1 subgroup (control = 1276.16 N ± 169.75; IP = 1211.70 N ± 281.64) compared with the 2.5:1 (control = 815.22 N ± 185.58, $P < 0.001$; IP = 621.68 N ± 186.28, $P < 0.001$) and the 3:1 subgroup (control = 606.55 N ± 111.48, $P < 0.001$; IP = 465.95 N ± 68.57, $P < 0.001$). Only the 2.5:1 subgroup showed a significant reduction ($P = 0.037$) of the F_{max} between the controls and the IP implants. Most fractures were located in the platform area. Only 5 implants with IP of the 2:1 CIR subgroup had a different fracture location (4 fractures in the implant body and 1 in the prosthetic screw).

Conclusions: IP significantly reduces the fracture resistance of implants with a 2.5:1 CIR. The results also suggest that the CIR seems to be a more relevant variable when considering the resistance to fracture of implants, since significant reductions were observed when unfavorable CIR subgroups (2.5:1 and 3:1 CIR) were compared with the 2:1 CIR samples.

Keywords: Peri-implantitis, Dental implants, Compressive strength, Titanium, Implantoplasty

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Background

Implant failure appears to have several causes: biological, mechanical or iatrogenic [1–3]. Peri-implantitis (PI) is one of the major concerns among clinicians, as it may

affect 34% of patients and 21% of implants and lead to implant loss [4].

Several approaches to implant surface decontamination have been studied. They include air-powder abrasion, ultrasonic and manual debridement (using plastic, carbon stainless steel, graphite or titanium curettes), implantoplasty (IP), laser therapy and sterile saline rinses, among others [5–8]. Mechanical debridement has also been complemented by the use of a number of substances, such as citric acid, hydrogen peroxide, cetylpyridinium chloride, tetracycline, ethylenediamine tetraacetic acid or chlorhexidine [9]. IP is a common procedure that consists of polishing rough implant surfaces outside the bony envelope, making them less prone to bacterial accumulation, as surface roughness may be risk factor for peri-implant disease. IP is effective in the long term for arresting bone loss caused by PI, both alone and in combination with surgical regenerative procedures and does not seem to be associated with any biological or mechanical complication of importance [9–13]. However, thermal increases during the procedure that could affect the bone, lower resistance to fractures due to reducing the thickness of the implant walls, and the local and systemic biological repercussions that the dispersion of titanium particles might have in the long term have been signaled as potential problems of IP performance [14–19].

Increasing bone loss due to PI was shown to increase clinical crown-to-implant ratio (CIR), which, in turn, was reported to reduce the resistance to fracture of intact dental implants [20, 21]. Also, IP, which is often used as a part of the treatment of PI, reduces the thickness of the implant walls and might weaken the strength of implants [15]. Since the effect of the CIR on implants treated with IP has not been addressed yet, it would be of great interest to assess whether IP is a safe technique when implants with high CIRs are involved. Furthermore, since the maximum failure strength of bone level implants is expected to remain high after IP, narrow implants were selected to simulate an unfavorable scenario. Indeed, according to a recent report by Bertl et al., narrow diameter implants have a significant lower resistance strength compared with regular diameter implants [22].

The main study hypothesis was that a high CIR negatively affects the fracture resistance of narrow implants treated with IP in a situation of 50% bone loss. Therefore, the main objectives of this research were: (1) to analyze whether an increased CIR reduces the fracture resistance of implants with IP versus control implants, and (2) to assess whether implants subjected to IP are more prone to fracture in comparison with control implants, regardless of the CIR, in the presence of 50% bone loss. A secondary aim was to describe the changes in implant wall width after IP.

Materials and methods

An in vitro study was conducted using 48 type V titanium narrow platform implants, 3.5 mm in diameter and 15 mm long, with a rough surface and a hexagonal external connection (Ocean E.C., Avinent Implant System S.L., Santpedor, Spain). Half of the sample was randomly allocated to the IP group. The apical half of each implant was inserted, leaving 7.5 mm exposed, in standardized bone-like resin casts (EA 3471 A and B Loctite®, Henkel AG and Company, Düsseldorf, Germany) with a $\geq$ 3 GPa modulus of elasticity in accordance with International Organization for Standardization (ISO) standard 14801:2016 (third edition) [23]. Both groups were divided into 3 subgroups of 8 implants each, which received screwed hemispherical loading abutments of one of three heights: 7.5 mm, 11.25 mm and 15 mm, simulating clinical CIR of 2:1, 2.5:1 and 3:1, respectively (Fig. 1).

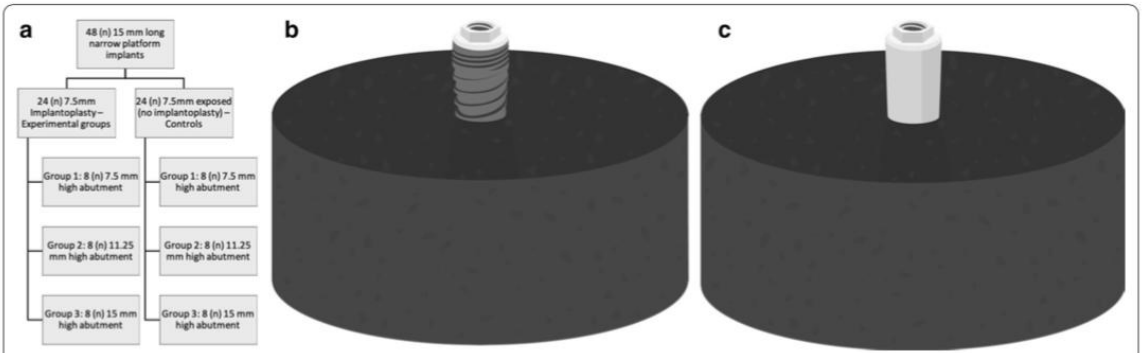

Fig. 1 **a** Study design, groups and subgroups; **b** sample before IP; **c** sample after IP

Implantoplasty

IP of the exposed implant surface was performed using a high-speed air-powered hand piece (Bora Blackline LED, Bien-Air Dental SA, Langgasse, Switzerland) with an abutment protecting the connection. After removing the threads of the exposed portion of the implants, using an oval-shape tungsten carbide bur (H379 314,023; Komet Dental, Lemgo, Germany), the surface was polished with two-step silicon carbide polishers (9618,314,030 and 9608,314,030; Komet Dental, Lemgo, Germany) until it was macroscopically flat and smooth. A new set of burs was used for each sample. The procedure was performed by an experienced surgeon with 2.8 × magnification loupes (Galilean HD and Focus™ LED 6000 k, ExamVision ApS, Samsø, Denmark), under copious water irrigation and adequate light conditions, similar to a clinical scenario, although the cast was held by the operator and turned by hand. The time spent on each procedure was recorded. When the IP procedure was finished, the surface was cleaned with water and dried with air.

Radiographic implant wall width measurements

The implant wall width was measured through plain x-ray examination of all the samples, in the initial position and rotated through 120° and 240°, using standardized mounts. All the measurements were made using ImageJ v.1.51 (National Institutes of Health, Bethesda, Maryland, USA), based on a fixed 1.9 mm reference provided by the manufacturer. A calibrated investigator (BLA) performed the examination with 400X amplification and searched for perforations of the implant walls. The measurements were made at the middle of the first (R1) and tenth (R2) threads and at the end of the prosthetic screw hole (R3), as shown in Fig. 2. To test intraexaminer agreement and consistency, the assessment of 6 randomly selected samples (54 measurements) was repeated after 2 weeks. The intraclass correlation coefficients were 0.96 (95% confidence interval (95%CI) 0.93–0.98; $P < 0.001$) and 0.96 (95% CI 0.92–0.98; $P < 0.001$), showing excellent reliability and consistency.

The mean value of the three measurements (rotation of 0°, 120° and 240°) was recorded for each location and implant. The measurements in the IP group were subtracted from those of their control analogues, thus obtaining the thinning of the implant for each variable.

Fracture tests

Metallic hemispherical load abutments (n = 48) were digitally designed, milled and screwed onto each implant according to subgroup (Fig. 3a–c), using prosthetic screws (Avinent® Implant System, Santpedor, Spain) at 32 N/cm, as recommended by the product manufacturer.

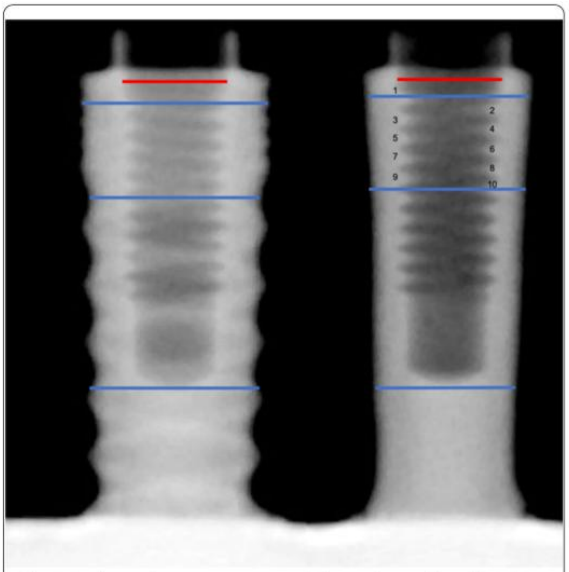

Fig. 2 Radiographic measurements of the implant wall width. Left: control implant; right: IP implant. Blue lines: length at middle of the first (R1) and tenth (R2) threads and at the end of the prosthetic screw hole (R3), perpendicularly to the long axis of the implant; red line: 1.9 mm reference

Tests to measure the maximum compression force (F_{max}), i.e. the maximum force reached before implant fracture, were performed at a constant speed of 1 mm/min with a universal servo-hydraulic mechanical testing machine (MTS Bionix 370 Load Frame, MTS®, Eden Prairie, USA), applying a compression load to the implants with a 661.19H-03 MTS Load Cell of 15 kN capacity. All the samples were held in the same device, a manufactured stainless-steel clamping jaw that allowed compression loads to be applied at a constant angle of 30° from the vertical axis (Fig. 3d), in accordance with ISO 14801:2016 (third edition), except for the supracrestal 50% of the total implant length. The tests were monitored by the MTS Flextest 40 Controller (MTS®, Eden Prairie, USA), which measured F_{max} and recorded real-time data.

Scanning electron microscopy (SEM) (Quanta 200®, FEI, Hilsboro, Oregon, United States) screening of the fractured implants was used to determine the fracture location.

Statistical analysis

The sample size calculation was performed with Stata v.14 software (StataCorp®, College Station, USA). Considering F_{max} as the primary outcome measure, an analysis of variance with an α risk of 0.05 and a statistical power of 80% was performed. The mean fracture resistance values published by Gehrke [24] were used.

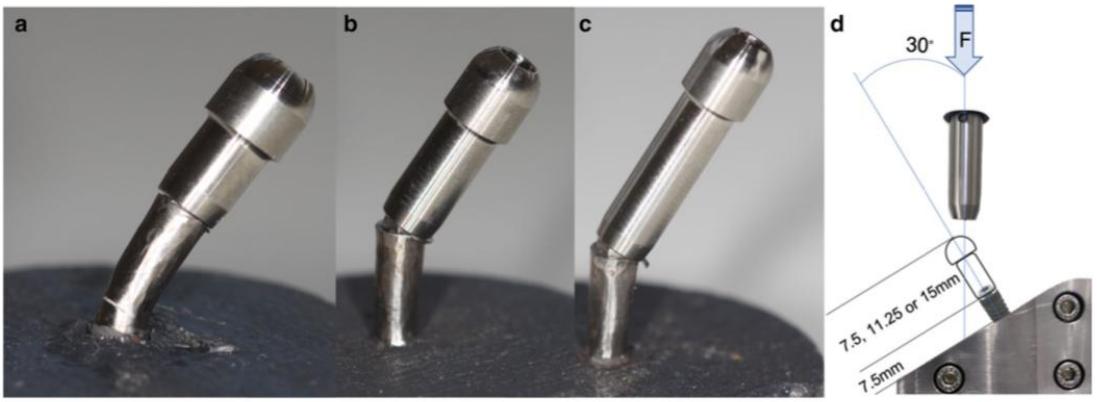

Fig. 3 IP samples after fracture test: **a** CIR 2:1, **b** CIR 2.5:1, **c** CIR 3:1, **d** fracture test diagram

Assuming a standard deviation of 500 N, the sample size was established as 8 implants per subgroup.

The implant characteristics were presented as absolute and relative frequencies for categorical outcomes. The normality of the scale variables (F_{max} and implant wall width) was explored using the Shapiro–Wilk test, P–P scatterplot graphs and box plots. Since F_{max} and the implant wall width variables had a normal distribution the mean and the standard deviation (SD) were used.

To analyze the effects of the procedure (IP or control) on F_{max}, of the crown length (7.5, 11.25 or 15 mm), and of the interaction between these two variables, a two-way ANOVA was performed. The ANOVA assumptions were assessed using the Shapiro–Wilk test for normality and Levene's test for homoscedasticity. Pairwise comparisons between subgroups, using Tukey's correction for multiplicity of contrasts, were made for each procedure and CIR. An unpaired *t* test was used to identify differences in implant wall width between the control and IP groups at every reference point. In each area of interest, Pearson correlation coefficients were computed to quantify the correlation between implant wall width and F_{max}. The associations between categorical variables were assessed with either Pearson's χ^2 test or Fisher's exact test.

The statistical analysis was carried out with Stata14 software (StataCorp®, College Station, TX, USA). The level of significance was set at $P < 0.05$.

Results

Fracture tests

No correlations between implant wall width measurements and F_{max} were observed at any of the reference points (Table 1). Significant reductions in F_{max} between the control and IP implants were only found in the 2.5:1 CIR subgroup ($P = 0.037$), although all the IP samples showed less resistance to fracture than their respective controls (Table 2, Fig. 4). In both IP and control groups, the implants with a 2:1 CIR showed a higher F_{max} (control = 1276.16 N ± 169.75; IP = 1211.70 N ± 281.64) than those with a 2.5:1 CIR (control = 815.22 N ± 185.58; IP = 621.68 N ± 186.28) and 3:1 CIR (control = 606.55 N ± 111.48; IP = 465.95 N ± 68.57). No significant differences were observed between the 2.5:1 and 3:1 subgroups (control $P = 0.064$; IP $P = 0.206$) (Table 3, Fig. 4).

Most fractures (n = 43) were located in the platform area (Fig. 5a, b). The only 5 exceptions were found in implants with IP of the 2:1 CIR subgroup [4 fractures in the implant body (Fig. 5c) and 1 in the prosthetic screw (Fig. 5d)].

Radiographic implant wall width measurements

The mean reduction in the implant wall width after IP was 0.41 (CIR 2:1), 0.41 (CIR 2.5:1) and 0.37 mm (CIR 3:1) at R1; 0.46 (CIR 2:1), 0.45 (CIR 2.5:1) and 0.46 mm (CIR 3:1) at R2 and 0.45 (CIR 2:1), 0.43 (CIR 2.5:1) and 0.4 mm (CIR 3:1), at R3 (Table 1). In all the subgroups, IP was associated with a statistically significant reduction in width at reference points 1–3 ($P \leq 0.05$, independent samples *t* test) and a similar value was found at each reference point ($P > 0.05$ in all cases; one-way ANOVA) regardless of the crown length subgroup of the implant. No perforation of the inner threads of the implants were observed.

Table 1 Implant wall width measurements (mm) of IP and control samples at each reference point (n = 48)

Reference point	Control	IP			
	Mean (SD)	Mean (SD)	MD (95%CI)	Independent samples *t* test *P* value	ANOVA *P* value
R1 (first thread)					
2:1	3.44 (0.02)	3.03 (0.04)	0.41 (0.37–0.44)	< 0.001*	0.103
2.5:1	3.44 (0.01)	3.03 (0.04)	0.41 (0.38–0.45)	< 0.001*	
3:1	3.45 (0.02)	3.08 (0.04)	0.37 (0.33–0.40)	< 0.001*	
R2 (tenth thread)					
2:1	3.32 (0.03)	2.86 (0.03)	0.46 (0.42–0.49)	< 0.001*	0.949
2.5:1	3.31 (0.02)	2.86 (0.04)	0.45 (0.41–0.49)	< 0.001*	
3:1	3.34 (0.03)	2.89 (0.06)	0.46 (0.41–0.50)	< 0.001*	
R3 (end of the prosthetic screw hole)					
2:1	3.07 (0.03)	2.62 (0.06)	0.45 (0.40–0.50)	< 0.001*	0.163
2.5:1	3.07 (0.05)	2.64 (0.04)	0.43 (0.38–0.47)	< 0.001*	
3:1	3.07 (0.02)	2.68 (0.04)	0.40 (0.36–0.43)	< 0.001*	

* Statistically significant difference

MD mean difference (Control—IP)

Table 2 Mean fracture strength (N) of the three CIR in the IP and control samples

CIR	Control	IP		
	Mean (SD)	Mean (SD)	MD (95%CI)	Adjusted *P* value
2:1	1276.16 (169.75)	1211.70 (281.64)	64.46 (− 117.17 to 246.09)	0.478
2.5:1	815.22 (185.58)	621.68 (186.28)	193.54 (11.91–375.17)	0.037*
3:1	606.55 (111.48)	465.95 (68.57)	140.60 (− 41.03 to 322.24)	0.126
Total	899.31 (323.58)	766.44 (379.19)	132.87 (− 71.95 to 337.69)	0.198

* Statistically significant difference

MD mean difference (Control—IP)

Discussion

The main objectives of this in vitro study were to determine if narrow platform titanium implants with an external hexagonal connection subjected to IP were more prone to fracture in the presence of 50% bone loss, and to analyze if an increased CIR reduces the fracture resistance of implants with IP *vs.* control implants. The results of the present study show that IP only significantly reduced the F_{max} value in the 2.5:1 CIR subgroup. Besides, the mean total values of the 3 CIR subgroups showed no significant differences in F_{max} between the control and IP samples (Table 2). CIR seems to be a much more relevant variable than IP, since both the IP and control implants showed significant reductions in F_{max} in the 2.5:1 and 3:1 CIR subgroups when compared to the 2:1 subgroup (Table 3). Indeed, while IP reduced the mean fracture strength by 132.87 N, a higher CIR (2.5:1 or 3:1) led to a mean difference of 525.48 N or 707.68 N, respectively (Tables 2, 3).

Similar in vitro protocols have been described previously, although with different implants, bone insertion levels and loading abutments [15, 24–27]. Shemtov-Yona et al. used intact 13 mm-long implants with different widths and performed similar static tests, finding F_{max} values of 674 N ± 57 (3.3 mm implants), 952 N ± 103 (3.75 mm implants) and 1584 N ± 115 (5 mm implants), showing that implant wall width can affect resistance outcomes of intact implants [28]. On the other hand, Chan et al. using internal hexagonal implants, compared control and IP samples with different widths (3.75 and 4.7 mm) and showed that IP did not significantly affect the resistance to fracture of 3.75 diameter implants (321.7 N ± 21.4 vs. 325.0 N ± 20.7) [15]. The fact that our report presents higher F_{max} values (Table 2) might be considered surprising since the implant diameter was inferior (3.5 mm), the CIRs were unfavorable and the simulated bone level was of 50%. This discrepancy might be justified by the fact that our

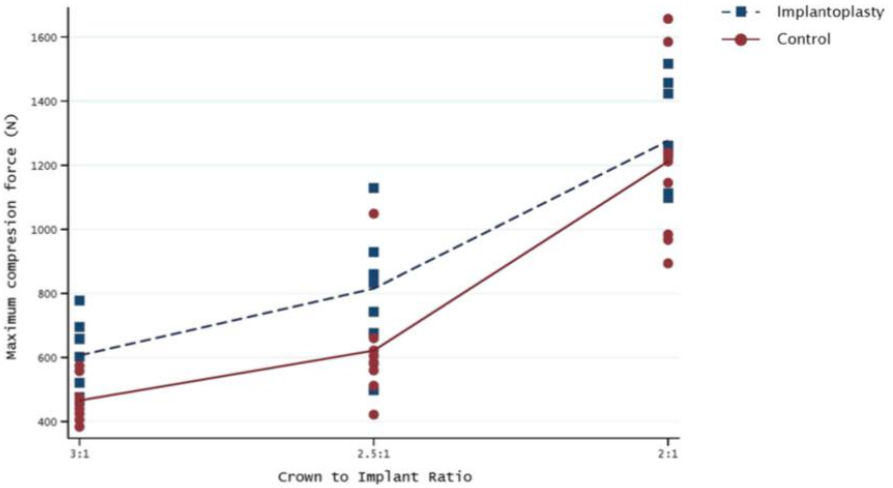

Fig. 4 Mean fracture strength (N) of the three CIR ratios in the IP and control samples

Table 3 Mean fracture strength (N) of the IP and control groups in the three clinical CIR subgroups

Group	CIR1	CIR2	MD (95% CI)	Adjusted *P* value
Control	2:1	2.5:1	460.94 (242.27–679.60)	<.001*
		3:1	669.60 (450.94–888.27)	<.001*
	2.5:1	3:1	208.67 (−9.99 to 427.33)	.064
IP	2:1	2.5:1	590.02 (371.36–808.68)	<.001*
		3:1	745.75 (527.09–964.41)	<.001*
	2.5:1	3:1	155.73 (−62.93 to 374.39)	.206
Total	2:1	2.5:1	525.48 (363.58–687.38)	<.001*
		3:1	707.68 (545.78–869.57)	<.001*
	2.5:1	3:1	182.20 (20.30–344.10)	<.001*

* Statistically significant difference

MD mean difference (CIR1—CIR2)

study employed external hexagonal implants which have shown higher F_{max} values in comparison with internal hexagonal implants in a recent published paper [26].

Significant differences in implant wall width due to the IP procedure were observed at all the reference points, but no perforations of the inner threads were found. The reduction in implant diameter at each of the 3 reference points ranged from 0.37 mm (95% CI 0.33–0.40 mm) to 0.46 mm (95% CI 0.41–0.50 mm) in the IP test samples. Other authors with similar IP protocols have reported lower reductions [25, 29]. These discrepancies might be explained by differences in the degree of polishing, but are more likely to be the result of different implant geometries, namely thread depth and model. Thus, further studies with different implants should be carried out, since their design and material are likely to affect the implant's resistance to fracture. A similar extent of change was found at each reference point ($P > 0.05$ in all cases; one-way ANOVA), regardless of the crown length subgroup of the implant, showing the similarity of the IP across all these samples, which would indicate that the procedure should be easy to reproduce.

Previous reports have claimed that implant diameter affects stress fatigue behavior and that dental implants will attain a critical stress point at lower loadings when subjected to IP [15, 27, 28]. The present results corroborate this finding, as lower resistance to fracture was observed in the IP groups (Table 2). All the IP groups showed less F_{max} values than the control groups, although these differences were found to be significant in only one of the CIR subgroups (2.5:1). Hence, narrow platform implants seem to be structurally weakened by IP procedures, although the most relevant risk factor for mechanical complications in the presence of 50% of bone loss seems to be CIR, as the mean F_{max} values dropped to almost half between the 2:1 and 2.5:1 CIR subgroups (mean difference 590.02 N, 95% CI: 371.36 N to 808.68 N) and by 61.6% between 2:1 and 3:1 (mean difference 745.75 N, 95% CI: 527.09 N to 964.41 N) (Table 3). Bertl et al. [22] having obtained a statistically significant reduction of fracture resistance on IP implants, reported that the forces required to fracture or deform a narrow diameter implant with IP remained high and therefore,

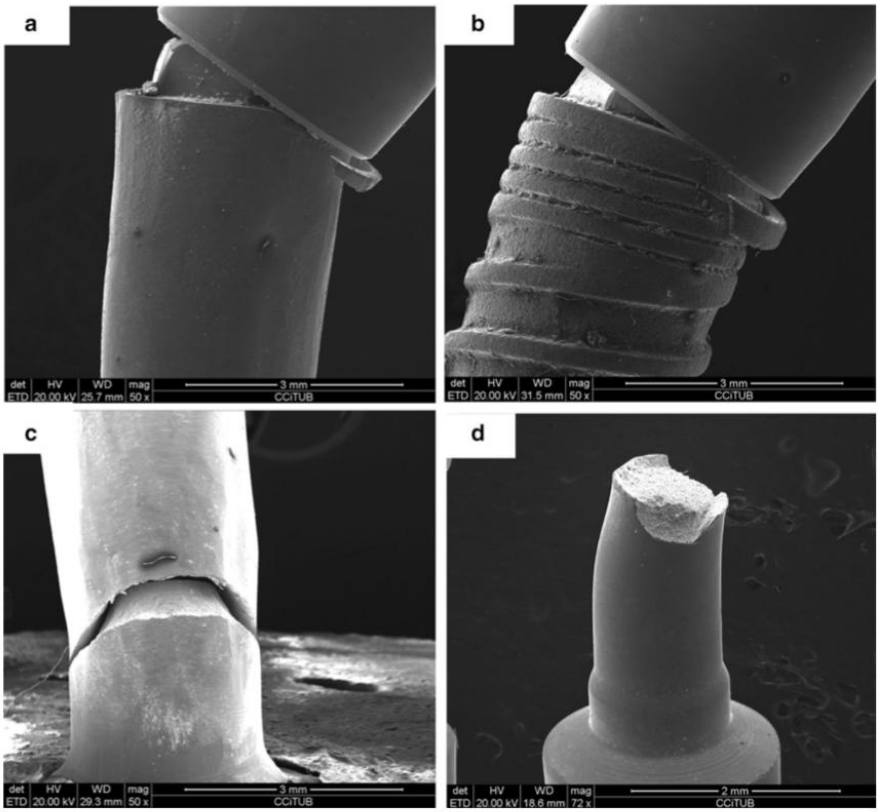

Fig. 5 SEM screening: **a** IP sample platform fracture; **b** control sample platform fracture; **c** IP sample body fracture; **d** prosthetic screw fracture;

this reduction has a limited clinical relevance in the majority of cases.

In both the IP and control groups, F_{max} decreased with increasing CIR, although the only significant differences were between CIR 2:1 and the other two subgroups (Table 3). No significant differences between CIR 2.5:1 and 3:1 were observed despite the latter's resistance to fracture being lower in both the IP and control implants (Control: 815.22 N vs. 606.55 N; IP: 621.68 N vs. 465.95 N). This outcome might be related with the limited sample size and with the observed standard deviations. However, it is important to stress that the lowest resistance value was found in the 3:1 CIR subgroup with IP (465.95 N ± 68.57).

In the present study, the area mostly affected by fracture was the platform, which would suggest that the platform is more fragile than the body in narrow fixtures. While all the control implants broke at the platform, in the IP group with a 2:1 CIR some fractures occurred in the body (n = 4) and prosthetic screw (n = 1), suggesting that IP reduces the mechanical resistance of the implant body. However, when higher CIRs were tested the stress seemed to be directed towards the platform and the prosthetic connection, and therefore all the fractures occurred in this area. Other studies using regular platform implants have found that implants subjected to IP usually break at the implant body, and although IP does not seem to decrease the maximum compression force of regular diameter external connection implants significantly, it clearly weakens the implant body [25]. Upon testing different CIRs with 3.5 mm intact external hexagon implants, fracture screw and implant platform deformation have been reported along with reduced resistance to fracture with increasing CIR. Gehrke performed an in vitro study with 60 implants with 3 different connections and also concluded that increasing the crown height significantly reduces the resistance to loading [24]. According to this paper, the abutment connection type also seems to be a relevant variable in

the fracture resistance of dental implants, since morse taper implants seem to be less prone to fracture than external and internal hexagonal connections. However, IP may alter these results. Indeed, a recently published paper compared the fracture resistance after IP of three connection designs and concluded that external hexagonal connection implants have a higher resistance to fracture [26]. Another variable that should be taken into consideration is the degree of bone loss. This factor might be relevant since it affects the clinical crown height [30].

The present study presents some limitations related to its in vitro design. Firstly, the IP procedures were performed by hand to simulate real-life conditions, instead of using a milling machine. Although this might compromise the standardization of the implant reduction slightly, it increased the external validity of the outcomes. Secondly, long implants (15 mm) were selected in order to assure adequate retention in the resin during the fracture tests. The length and 50% exposure of the implant provide information especially for extreme bone loss cases. In addition, 3.5 mm wide implants were selected because previous reports have shown that narrower implants must be addressed carefully for IP [15]. Nevertheless, narrow implants are widely used and bone loss from PI can affect any implant. Consequently, these factors were considered valuable for understanding the threshold of fracture resistance. Although a 15 mm long implant with a 15 mm long restoration is not common, considering a bone level type implant it represents a standard 1:1 CIR. Also, when PI has caused the loss of 5 mm of bone, the 1:1 clinical CIR of a 10 mm long implant with a 10 mm long restoration becomes a clinical CIR of 3:1, similar to that of the 15 mm abutment subgroup in this study. In addition, the static compressive loads at a 30° angle used for fracture testing do not replicate the daily complex oral function of patients [31]. However, the methodology employed complied with ISO guideline 14801:2016 (third edition), except for the vertical exposure of the implant, allowing comparison with previous studies. Nevertheless, future research should include dynamic fatigue tests to determine the clinical relevance of the fracture resistance encountered. According to Gibbs et al., the maximum human clenching force covers a wide range, from 98 to 1243 N, and is affected by several factors including age, gender and tooth support [32]. The top of this range would fracture all the samples except for the controls with a 2:1 CIR [1276.16 N ($\sigma = 169.75$)].

Bite force seems to decrease from molar to premolar and to incisor. Maximum bite forces measured in male subjects are higher than those of female subjects according to Umesh et al. [33]. The same authors found maximum bite forces of 744 N in molars, 371 N in premolars and 320 N in incisors.

Considering the above outcomes and comparing them with the present data, IP procedures with a CIR of 2:1 (mean fracture strength 1211.70 N ± 281.64) would present a low fracture risk regardless of implant position, and fracture risk would be of concern after IP in molar regions with a CIR of 2.5:1 (mean fracture strength 621.68 N ± 86.28) or 3:1 (mean fracture strength 465.95 N ± 68.57).

In such cases, it would be advisable for clinicians to perform a risk–benefit analysis, since implant fractures are more likely to occur. Therefore, as the Young modulus of different titanium alloys and ceramic implants varies, further research is needed to determine the resistance to fracture of new materials used for dental implants.

Conclusions

IP significantly reduces the fracture resistance of implants with a 2.5:1 CIR. The results also suggest that the CIR seems to be a more relevant variable when considering the resistance to fracture of implants, since significant reductions were observed when unfavorable CIR subgroups (2.5:1 and 3:1 CIR) were compared with the 2:1 CIR samples.

Abbreviations

CIR: Crown-to-implant ratio; F_{max}: Maximum compression force; IP: Implantoplasty; ISO: International Organization for Standardization; PI: Peri-implantitis; R1: Length at middle of the first thread; R2: Length at middle of the tenth thread; R3: Length at the end of prosthetic screw hole; SD: Standard deviation; SEM: Scanning electron microscopy.

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Authors' contributions

BLA: design of the study; acquisition and interpretation of the data; drafting of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; RF: Conception and design of the study; interpretation of the data; drafting of the artic e; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; AC: Conception of the study; interpretation of the data; critical review of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; OCF: Conception of the study; analysis and interpretation of the data; critical review of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; JMM: Conception of the study; interpretation of the data; critical review of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; EVC: Design of the study; analysis and interpretation of the data; critical revision of the manuscript; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work. All authors read and approved the final manuscript.

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Ethics approval and consent to participate
This article does not report on any studies with human or animal participants and formal consent is not required.

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Not applicable.

Competing interests
The authors declare non-financial support from Avinent (Santpedor, Spais) for this study. The authors would like to declare the following interests outside the work presented: BLA reports personal fees (sponsored lectures) and non-financial support from Megagen (Daegu, South Korea) outside the submitted work. RF reports personal fees (sponsored lectures) from Inibsa Dental (Lliça de Vall, Spain). In addition, he has participated as a sub-investigator in a randomized clinical trial sponsored by Mundipharma (Cambridge, UK) and another clinical trial for Menarini Ricerche (Florence, Italy). AC reports personal fees (sponsored lectures) from Straumann (Basel, Switzerland). JMM reports no conflicts of interest. OCF reports grants, personal fees (sponsored lectures) and non-financial support from MozoGrau (Valladolid, Spain), and personal fees (sponsored lectures) from BioHorizons Ibérica (Madrid, Spain), Inibsa Dental (Lliça de Vall, Spain), Dentsply implants Iberia (Barcelona, Spain) and Araguaney Dental (Barcelona, Spain) outside the submitted work. He has also participated as a principal investigator in a randomized clinical trial sponsored by Mundipharma (Cambridge, UK) and in another clinical trial as a sub-investigator for Menarini Ricerche (Florence, Italy). EVC reports personal fees (sponsored lectures) and non-financial support from MozoGrau (Valladolid, Spain), and personal fees (sponsored lectures) from BioHorizons Ibérica (Madrid, Spain), Inibsa Dental (Lliça de Vall, Spain) and Dentsply implants Iberia (Barcelona, Spain) outside the submitted work. In addition, he has participated as a sub-investigator in a randomized clinical trial sponsored by Mundipharma (Cambridge, UK).

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Effect of bone loss on the fracture resistance of narrow dental implants after implantoplasty. An *in vitro* study

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Abstract

Background: Implantoplasty (IP) involves polishing of the exposed surface of implants affected by peri-implantitis (PI). A study was made to determine whether the degree of bone loss influences the fracture resistance of implants with or without IP.

Material and Methods: An *in vitro* study was carried out on 32 narrow (3.5 mm) dental implants with a rough surface and external hexagonal connection. Implantoplasty was performed in half of the implants of the sample. Both the IP and control implants were divided into two subgroups according to the amount of bone loss (3 mm or 7.5 mm). Standardized radiographic assessment of implant width was performed using specific software. The main outcome variable was the maximum compression force (F_{max}) of implants when subjected to static resistance to fracture tests. Implant fractures were subsequently analyzed by scanning electron microscopy. A descriptive and bivariate analysis of the data was performed.

Results: Significant changes in implant width were observed after IP ($p<0.05$). No significant differences between IP and control implants were recorded in terms of the F_{max} values in the two bone loss subgroups (3 mm: control 854.37N ± 195.08 vs. IP 752.12N ± 186.13; $p=0.302$, and 7.5 mm: control 548.82N ± 80.02 vs. IP 593.69N ± 111.07; $p=0.370$). Greater bone loss was associated to a decrease in F_{max}, which proved significant for the control implants ($p=0.001$). Fractures were more frequently located in the platform (n=13).

Conclusions: Implants with more apical bone levels appear to be more susceptible to fracture. On the other hand, IP does not seem to significantly decrease the fracture resistance of narrow (3.5 mm) platform dental implants with external hexagonal connections. The fact that most fractures occur in the platform area indicates that the latter is exposed to more mechanical stress.

Key words: *Peri-implantitis, dental implants, compressive strength, titanium, implantoplasty.*

Introduction

Peri-implantitis (PI) is a common disease that affects an important number of patients with dental implants (1,2). This complication leads to progressive peri-implant bone loss, creating defects of different anatomical characteristics, shapes and sizes (3).

Different approaches have been suggested for the treatment of PI, ranging from non-surgical to surgical options. Although a number of authors have described different resective and/or regenerative protocols, some controversy remains regarding the most effective treatment for PI (4–6). Non-surgical therapies seem to be mostly ineffective in preventing disease progression in the presence of moderate or severe PI, though some reports claim otherwise (7). On the other hand, surgical techniques are usually considered to be more predictable, since they seem to hinder the progression of bone loss (8,9).

Implantoplasty (IP) involves polishing of the exposed rough surface of implants presenting bone loss, with the purpose of detoxifying and smoothening these areas to prevent biofilm accumulation (6,10). However, a number of concerns have been raised, such as bone necrosis due to increased temperature, local and systemic toxicity of titanium particles released during IP, and a reduction of resistance to fracture (11,12). It is therefore important to determine whether IP is a safe technique that does not compromise the long-term prognosis of dental implants. Several *in vitro* reports seem to indicate that IP does not significantly reduce the mechanical resistance of dental implants (13,14). However, a number of other variables may also affect this parameter. For example, the amount of bone loss resulting from PI inevitably modifies the mechanical equilibrium of the implant-abutment-restoration complex, and can lead to complications related with the prosthetic components and implants (15). Indeed, bone loss together with other factors such as implant diameter, crown-to-implant ratio (CIR) and bruxism have been associated with an increased risk of dental implant fractures (16). The implant design and connection might also be important in relation to mechanical resistance (17,18). As mentioned, implants with bone loss often require IP. This procedure reduces the thickness of the implant walls, which in turn can weaken the implant (19). Based on finite element analysis, IP has been associated to a 10% decrease in implant resistance to fracture, independently of the bone level. Also, it is important to underscore that a critical threshold might be reached when more than half of the length of the implant has lost bone support (20).

Due to the scarcity of scientific data for supporting clinical decisions, an *in vitro* study was carried out to analyze the influence of bone loss upon the fracture resistance of narrow dental implants with hexagonal external connections with and without IP.

Material and Methods

An experimental *in vitro* study was made of 32 titanium-type V narrow platform (3.5 mm) dental implants measuring 15 mm in length, with a rough surface and a hexagonal external connection (Ocean E.C., Avinent Implant System S.L., Santpedor, Spain). Sixteen implants were randomly established as control group, while the remaining 16 served as the IP group. In turn, two additional subgroups of 8 implants each were established according to the amount of simulated bone loss (3 mm or 7.5 mm) (Fig. 1).

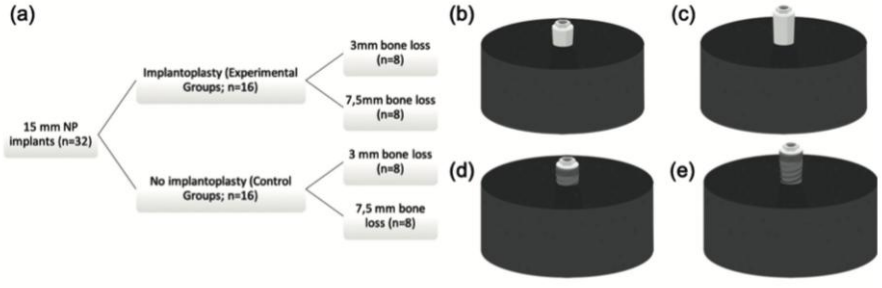

Fig. 1: (a) Study design, groups and sub-groups; (b) 3 mm IP sample; (c) 7.5 mm IP sample; (d) 3 mm control sample; (e) 7.5 mm control sample. NP: narrow platform.

All implants were embedded in standardized bone-like resin casts (EA 3471 A and B Loctite®, Henkel AG & Company, Düsseldorf, Germany) with ≥ 3 GPa modulus of elasticity according to the International Organization for Standardization (ISO) 14801:2016 (third edition) (Fig. 1), and received a customized hemispherical loading abutment. The protocol used is similar to that described in a recent paper (14).

- Implantoplasty

Implantoplasty was performed according to the technique described by Costa-Berenguer *et al.* (13). In short, an oval-shaped tungsten carbide bur (H379 314 023; Komet Dental, Lemgo, Germany) and two silicon carbide polishers (9618 314 030 and 9608 314 030; Komet Dental, Lemgo, Germany) were used to remove and polish all the exposed areas of each implant with a high-speed handpiece. The procedure was performed by an experienced surgeon (BLA) with 2.8x magnification loupes (Galilean HD and Focus™ LED 6000k, ExamVision ApS, Samsø, Denmark).

- Radiographic assessment of implant width

Modifications of implant width were evaluated radiographically according to the procedure described by Camps-Font *et al.* (21) using plain X-rays and then rotating them 120º and 240º using standardized mounts. All measurements were performed with ImageJ v.1.51 (National Institutes of Health, Bethesda, MD, USA) by a calibrated investigator (BLA) under 400x amplification. Six random implants were assessed twice to test intra-examiner agreement and consistency. The intraclass correlation coefficients (ICCs) were 0.96 (95% confidence interval (95%CI) 0.93 to 0.98; $p<0.001$) and 0.96 (95%CI 0.92 to 0.98; $p<0.001$).

Three reference areas were selected for the measurements: length at the middle of the first thread (R1), tenth thread (R2) and at the end of the prosthetic screw hole (R3), perpendicular to the long axis of the implant. Reference point R3 could not be assessed in the 3 mm subgroup, because this area was embedded in radiopaque resin. The mean measurements of the IP group were subtracted from their control analogues, thus obtaining mean reduction of the implant at each reference point.

- Fracture tests

Resistance to fracture tests were performed in each group to determine the maximum compression force (F_{max}) reached before implant fracture occurred (main outcome variable). This procedure was similar to that described by Leitão-Almeida *et al.* (14), except for the amount of implant inserted in the resin and the length of the load abutment. In brief, 7.5 mm-high metal hemispheric load abutments (n=32) were placed on each implant using prosthetic screws (Avinent® Implant System, Santpedor, Spain) at 32 N/cm. All tests were performed in accordance with the UNE-EN ISO 14801:2016 (third edition) guideline parameters, except for supracrestal exposure of the 7.5 mm subgroup. A universal mechanical testing machine (MTS Bionix 370 Load Frame; MTS®, Eden Prairie, USA) applied compression force to the implants with an MTS Load Cell 661.19H-03 of 15 kN capacity. Compression forces were applied at a constant angle of 30 degrees from the vertical axis. Tests were controlled using MTS Flextest 40 (MTS®, Eden Prairie, USA) that recorded real-time data and measured F_{max}.

A descriptive analysis of the fractured implants was made from photographs taken with a scanning electron microscope (SEM) (Quanta 200®, FEI, Hilsboro, OR, United States).

- Statistical analysis

Previous results from Gherke *et al.* (17) were used to perform the sample size calculation using Stata v.14 (StataCorp®, College Station, USA). Considering F_{max} as the primary outcome measure, an analysis of variance (ANOVA) with an α risk of 0.05 and a statistical power of 80% was performed. Assuming a standard deviation of 500 N, the sample size was established as 8 implants per group.

Scale variables (F_{max} and implant width) were explored with the Shapiro-Wilk test, P-P scatter plots and box plots. The interquartile range (IQR) and median were reported when normal data distribution was rejected. The mean and standard deviation (SD) were employed in the presence of a normal distribution.

To analyze the effect of the group (IP or control) and subgroup (bone loss of 3 mm or 7.5 mm) upon F_{max}, and the interaction between these two variables, two-way ANOVA was performed. The ANOVA assumptions were assessed using the Shapiro-Wilk test for normality and Levene's test for homoscedasticity. Pairwise comparisons were made using Tukey's correction for multiplicity of contrasts. An unpaired t-test was used to identify differences in implant width between control and IP implants. In each area of interest, Pearson correlation coefficients were computed to quantify the correlation between implant width and F_{max}. Pearson's χ^2 test or Fisher's exact test were performed for categorical variables.

The statistical analysis was carried out with Stata14 (StataCorp®, College Station, TX, USA). The level of statistical significance was set at $p < 0.05$.

Results

- Fracture tests

No correlations were observed between implant wall width and F_{max} at any of the reference points (Fig. 2). There was no significant decrease in F_{max} when comparing control and IP samples within the same bone loss subgroup (3 mm: control 854.37N ± 195.08, IP 752.12N ± 186.13, $p=0.302$; 7.5 mm: control 548.82N ± 80.02, IP 593.69N ± 111.07, $p=0.370$) (Table 1, Fig. 3).

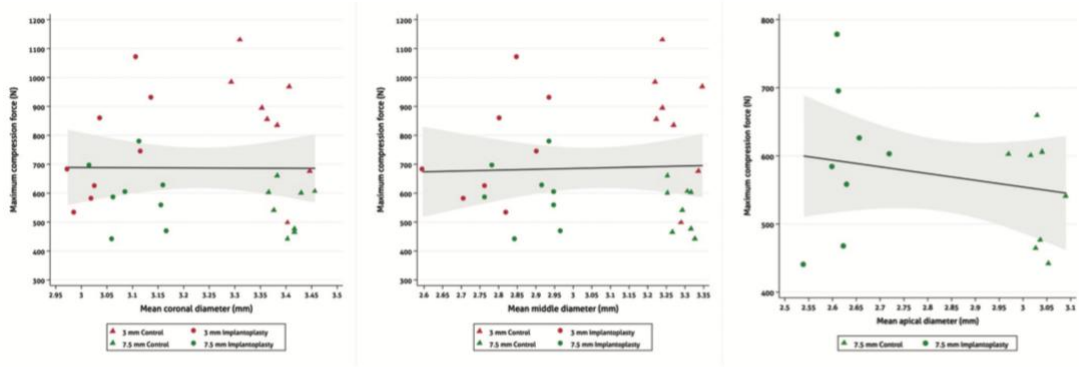

Fig. 2: Scatter plot assessing the relationship between maximum compression force (F_{max}) and mean sample diameter.

Table 1: Mean fracture resistance (N) of the bone loss subgroups in IP and control implants.

Bone loss subgroup	**Control**	**IP**	**Total sample**	**MD (95%CI)**	***P*-value**
3 mm Mean (SD)	854.37 (195.08)	752.12 (186.13)	803.25 (191.61)	102.24 (-102.21 to 306.70)	0.302
7.5 mm Mean (SD)	548.82 (80.02)	593.69 (111.07)	570.85 (96.45)	-44.87 (-148.69 to 58.94)	0.370
MD (95%CI)	305.54 (145.65 to 465.43)	158.43 (-5.94 to 322.79)	232.40 (121.22 to 343.58)		
P-value	.001*	.058	<.001*		

*Statistically significant difference (p<0.05); MD: mean difference (control - IP); 95%CI: 95% confidence interval.

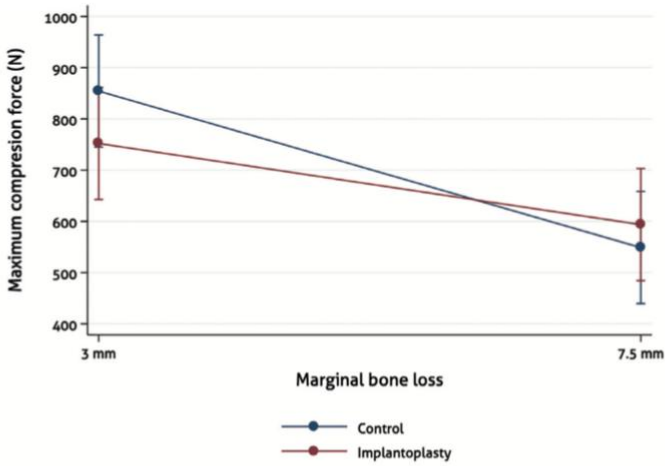

Fig. 3: Relationship between maximum compression force (F_{max}) and the amount of bone loss.

A significant decrease in F_{max} was observed in the 7.5 mm bone loss subgroup in the control samples (mean difference (MD) 305.54N ± 145.65-465.43, p=0.001), and the effect of IP was similar in each bone loss subgroup (Table 1, Fig. 3).

All control and 13 of the 16 IP implants fractured at platform level (Fig. 4). In the IP group, two implant body (Fig. 4) and one prosthetic screw fractures were also observed (Fig. 4).

- Radiographic assessment of implant width

The mean reductions in implant width after IP are reported in Table 2. Implantoplasty was associated to a statistically significant decrease in width at the observed reference points in all subgroups ($p \leq 0.05$, independent samples t-tests). The magnitude of the decrease was also similar across the bone level subgroups (p > 0.05, one-way ANOVA).

No correlations were observed between implant wall width and F_{max} at any of the reference points (Fig. 2). There were no perforations of the inner threads in any of the samples.

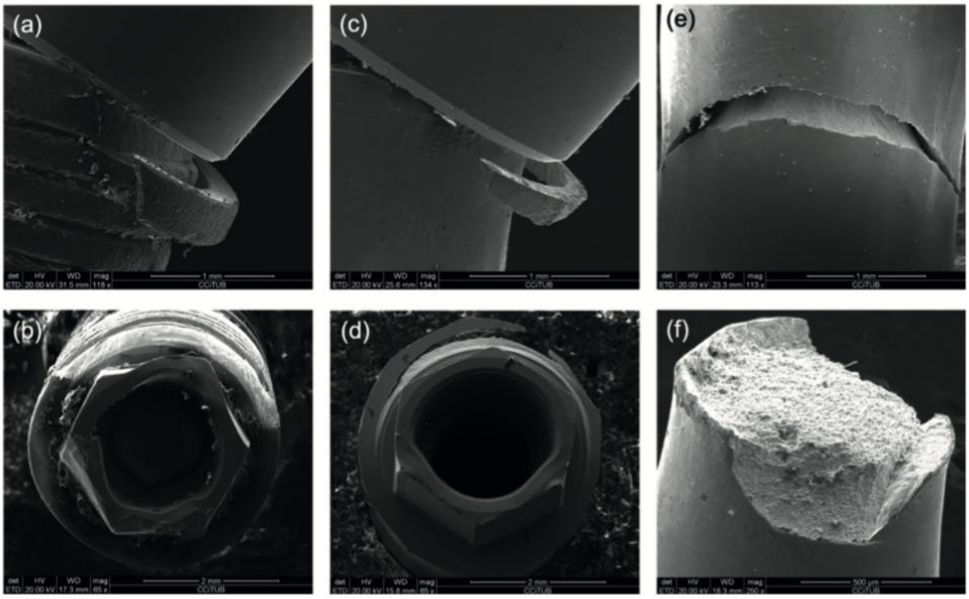

Fig. 4: Scanning electron microscopy. (a) Lateral view of a control sample platform fracture; (b) Upper view of a control sample platform fracture; (c) Lateral view of an IP sample platform fracture; (d) Upper view of an IP sample platform fracture; (e) Detail of implant body fracture in an IP sample; (f) Detail of prosthetic screw fracture.

Table 2: Mean implant width (mm) in the IP and control groups at each reference point (n=32).

	Control	IP			
Reference point	**Mean (SD)**	**Mean (SD)**	**MD (95%CI)**	**Unpaired t-test *P*-value**	**ANOVA *P*-value**
R1 (Length at the middle of the first thread)					
3 mm	3.37 (0.05)	3.05 (0.06)	0.31 (0.26 to 0.38)	<0.001*	0.685
7.5 mm	3.41 (0.03)	3.10 (0.06)	0.30 (0.26 to 0.35)	<0.001*	
R2 (Length at the middle of the tenth thread)					
3 mm	3.27 (0.05)	2.80 (0.11)	0.47 (0.38 to 0.56)	<0.001*	0.223
7.5 mm	3.29 (0.03)	2.89 (0.08)	0.40 (0.34 to 0.47)	<0.001*	
R3 (Length at the end of the prosthetic screw hole)					
3 mm	NA	NA	NA	NA	NA
7.5 mm	3.03 (0.03)	2.62 (0.05)	0.41 (0.36 to 0.46)	<0.001*	

*Statistically significant difference (p<0.05); MD: mean difference (control - IP); 95%CI: 95% confidence interval; NA: not applicable.

Discussion

Based on the results obtained, IP does not seem to have a significant impact upon the resistance to fracture of narrow platform implants with an external hexagonal connection (Table 1). On the other hand, the amount of bone loss appears to be a relevant factor in relation to fracture resistance, since the F_{max} required to fracture implants in the 7.5 mm subgroups was significantly lower than in the 3 mm subgroups (3 mm: 803.25N ± 191.61; 7.5 mm: 570.85N ± 96.45; p<0.001) (Table 1). Thus, clinicians should be aware that narrow diameter implants with significant bone loss might be more likely to suffer fractures, and that IP does not seem to add any additional risk. Although the mean fracture resistance of IP implants decreased when bone loss increased, this decrease was not statistically significant. A possible explanation for this is that most fractures occurred in the coronal region of the implant (platform area), indicating that this appears to be the most fragile area. Future research should assess whether these results are also valid for internal connection implants.

As expected, a significant reduction in implant width was observed at all reference points due to the IP procedure. Several authors have emphasized that implant diameter affects fatigue behavior of the fixtures, and that IP probably reduces the forces required to reach a criti-

cal stress point (15,20,22). The present report appears to contradict this statement, however, since the mean F_{max} values of the control versus IP implants were similar. Nevertheless, it is important to stress that IP is not the only variable that should be considered when analyzing the mechanical resistance of dental implants with PI. Indeed, recent studies have shown that implants with internal connections or with an unfavorable CIR seem to be more susceptible to fracture, and that parafunctional habits, implant design and base material can also affect implant strength - thus indicating that these variables also need to be taken into account (13–15,21). Likewise, our results suggest that the amount of bone loss appears to be a more relevant parameter than IP. A reduction of 305.54 N (95%CI 145.65 to 465.43; p=0.001) was observed in the control implants when the bone level shifted from 3 mm to 7.5 mm. The IP implants also presented a difference of 158.43 N (95%CI -5.94 to 322.79; p=0.058) (Table 1), which is in accordance with previous reports on the impact of bone loss and increasing pocket depths upon dental implant fractures (16).

Using finite element analysis, Tribst *et al*. (20) found that implants with lower insertion levels might increase damage to the bone. Also, IP increases stress in the implant and prosthetic screw, and there is a critical threshold when the inserted part of the implant is smaller than the exposed part. Similar methodology was employed by other authors who also found that the implant embedding depth affects resistance to fracture (23). All these outcomes seem to be confirmed by the present study.

The platform area of narrow implants with hexagonal external connections seems to be more fragile than the body, since all control implants fractured at this point. In the 3 mm bone loss subgroup, all implants (n=16) fractured at platform level. However, in the 7.5 mm bone loss subgroups, two IP implants fractured in the body area and, in one case, the prosthetic screw broke - thus suggesting that IP might reduce mechanical resistance of the implant body with increasing bone loss. Consistent with the present findings, other authors have also reported deformations at the platform border in all tested samples, reinforcing the idea that the platform area might be more susceptible to increased forces (17). When regular platform implants are subjected to IP, body fractures are more common in comparison with those observed in control implants, thus suggesting that IP weakens the implant body (13).

Some important clinical messages might be drawn from the present results. On one hand, clinicians should be aware that deep peri-implant bone defects are a risk factor for implant fracture. On the other hand, even though IP reduces the thickness of the implant walls, it does not seem to decrease the resistance to fracture of the fixtures. One might argue that this study simulates a very adverse clinical situation. Indeed, it is uncommon to find single-unit narrow diameter fixtures with deep peri-implant bone defects in the daily practice. In our opinion, this can also be seen as an advantage since it probably indicates that IP is unlikely to affect the fracture resistance in more favorable scenarios where regular- or large-platform implants are involved. Also, splinted restorations supported by several narrow implants are likely to have a better mechanical behavior and therefore less risk of fracture (24).

The *in vitro* design of the present study implies a number of limitations. First of all, the IP procedures were not fully standardized. However, it is unlikely that this limitation could have affected the results, since the implant width radiographic analysis showed similar reductions for both subgroups. On the other hand, IP was performed while holding the implant with the hand. This fails to reproduce the real-life clinical scenario, where the access can affect the outcome of the technique. Nevertheless, this method has been used previously, so comparisons can be made with the results of other authors (13,14,21). Another possible drawback is related to the fact that static compressive load testing may fail to replicate the complex daily oral function of patients (25). However, this methodology was selected in order to comply with ISO guideline 14801:2016 (third edition). On the other hand, the use of dynamic fatigue tests would increase the external validity of the results, and should be considered in future research. Also, the present report only evaluated 3 mm- and 7.5 mm-high peri-implant horizontal bone defects. Still, these subgroups may be interpreted by clinicians as respectively representing initial or advanced peri-implantitis cases. Finally, different prosthetic materials might have an impact upon the mechanical dynamics of the implants, and additional studies are needed to assess these variables.

Within the limitations of the present *in vitro* study, advanced bone loss should be considered a risk factor when assessing the resistance to fracture of narrow diameter implants with external hexagonal connections. Although IP significantly reduces the thickness of the implant walls, it does not seem to significantly alter the mechanical resistance of dental implants with the abovementioned features.

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Conflict of interest
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Ethics

This article does not report on any studies with human participants or animals performed by any of the authors.

Authors contributions

BLA: Design of the study; acquisition and interpretation of the data; drafting of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; RF: Conception and design of the study; interpretation of the data; drafting of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; AC: Conception of the study; interpretation of the data; critical review of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; OCF: Conception of the study; analysis and interpretation of the data; critical review of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; JMM: Conception of the study; interpretation of the data; critical review of the article; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work; EVC: Design of the study; analysis and interpretation of the data; critical revision of the manuscript; approval of the final version of the manuscript and agreement to be accountable for all aspects of the work.

DISCUSSION

Discussion

Overall, the combined experiments depicted in this work aimed to evaluate mechanical changes that occur in 3.5 mm platform dental implants submitted to IP with different BL and CIRs, in a controlled environment. Both studies suggest that IP does not increase the risk of fracture of dental implants and that other variables such as the CIR or BL significantly affect the mechanical resistance of dental implants. Accordingly, clinicians should consider CIR and BL as relevant variables when assessing the risk of fracture in implants with PI requiring implantoplasty.

The high incidence of peri-implant diseases, that has been reported to affect up to 46% of all implants placed (71,90,151), suggests an increasing need to develop evidence-based treatment protocols for these complications.

IP seems to improve the prognosis of implants with PI by reducing surface roughness of dental implants leading to inhibition of the biofilm growth without compromising the biocompatibility of the titanium base material (152). Indeed, a 87% rate of implant survival has been reported over a 2-6 years of follow-up period when a combined resective-IP surgical treatment was applied (114). This combination seems more effective than resective surgery alone (104,115). Also, PI treatments that include IP have shown a significant decrease in clinical probing depth and bleeding/suppuration on probing over a 3-year follow-up period (116,153). There is also evidence that a resective surgical procedure with chemical decontamination using 0.12% chlorhexidine and 0.05% cetylpyridinium but without any implant surface modification does not seem to provide clinical benefit in comparison with placebo (154).

Romeo et al. (108) compared resective surgery without surface modification *vs.* resective surgery with IP on PI cases with probing depths of more than 4mm. Significantly better results were achieved in the experimental group thus suggesting that more favourable

outcomes are expected when IP is performed. Laser therapy also seems to be a good alternative. Indeed, Pommer et al. (155) showed similarly high success rates (around 89%) using either IP or laser (155).

On the other hand, recent studies failed to find a significant effect of IP on the survival rate of the implants (117). A recent retrospective clinical study (117) has claimed that the BL at the time of surgical treatment seems to be a more reliable predictor of implant survival in comparison with IP. These authors also found that changes in clinical parameters such as marginal BL, bleeding on probing, pocket depth and suppuration were related to the regularity of supportive peri-implant care and not to the use of IP.

Typically, IP is performed using diamond or carbide burs followed by silicone polishers. Ramel et al. (156) compared six IP protocols and concluded that the best outcome was attained using rotary diamond burs with decreasing roughness followed by an Arkansas stone. All the tested options had a higher surface roughness in comparison with machined surfaces (156). In the present thesis, a simplified IP sequential protocol that employed an oval-shaped tungsten carbide bur followed by a two-step polishing with silicone carbide burs was used. This protocol has been described by Costa-Berenguer et al. (120) with good results in terms of final surface roughness.

Some authors have raised concerns regarding IP namely the reduction of the mechanical properties of the implant core or the connection system, thermal injury to the surrounding bone, staining of the surrounding mucosa and inflammatory reaction associated with the release of titanium particles. However, to the best of our knowledge, the available evidence does not suggest any relevant mechanical or biological complications associated with IP on the short- and medium-term, provided that the procedure is done correctly (123). In fact, regarding mechanical complications, although IP has been previously

associated with significant reduction in the width of implant walls no perforations of the inner threads are expected, in line with the results of the present studies (120,157).

In the first study of this thesis, the mean total values showed no significant differences in the fracture resistance between control (95%CI: 899.31N±323.58) and IP samples (95%CI: 677.44N ±379.19), although in the CIR 2.5:1 subgroup, IP implants showed a significantly lower maximal compression force (95%CI: 815.22N±185.58 *vs.* 621.68N±186.28 p=0.037). A significant reduction in mechanical resistance was observed in the 2.5:1 and 3:1 subgroups in both IP and control implants when compared to 2:1 subgroup, in accordance to previous reports (150). This seems to suggest that the CIR is a much more relevant variable than IP. In fact, while IP reduced the mean fracture strength by 132.87 N, a higher CIR (2.5:1 or 3:1) led to a mean difference of 525.48 N or 707.68 N, respectively.

In the second study of this thesis, there was also no significant reduction of resistance to fracture when comparing control and IP implants in each subgroup (3mm: 854.37N±195.08 *vs*. 752.12N±186.13; p= 0.302 and 7.5mm: 548.82N±80.02 *vs.* 593.69N±111.07; p=0.370). On the other hand, BL seems to be a much more important variable considering that a reduction of 305.54 N (95% CI: 145.65 to 465.43; p=0.001) was observed in the control groups when BL was increased from 3 to 7.5mm. The IP implants also showed a difference of 158.43 N (95%CI: -5.94 to 322.79; p= 0.058) in the same manner. Both observations are in line with previous papers regarding the impact of increased BL and pocket depth on dental implant fractures (158). For example, an *in vitro* protocol with intact implants and a dynamic loading protocol performed by Suzuki et al. (134) showed that the number of loading cycles needed for an implant to fracture seem to decrease in proportion to increased loading forces and decreased implant embedment depths.

Some reports state that dental implants with IP will reach a critical stress point at a lower loading (136,159). However, according to our results, this lower resistance to fracture does not seem to be statistically nor clinically significant when 3.5-mm-wide platform dental implants are involved. Nonetheless, it should be emphasized that when the involved implants have high CIRs and/or advanced BL, the development of mechanical complications might be more likely.

Camps-Font et al. (45) reported that the fracture resistance after IP is affected by implant-abutment connection design and that narrow implants with internal hexagon or conical connection designs are more prone to fracture when compared with hexagonal external connections. The connection design might be the reason why our results do not support those of Chan et al. (136), who found 3.75mm-wide implants with internal hexagonal connection to be significantly weakened by IP using a simulated 50% BL *in vitro* model. This confirms the need to perform additional research on this topic since different implant systems require testing. Another important variable that must be considered is the implant diameter. In the present studies, narrow-diameter implants were used to simulate an unfavourable clinical scenario. IP will probably have a smaller impact on the maximal compression forces of regular and wide platform implants. Indeed, Chan et al. (136) observed that IP did not affect the mechanical properties of 4.7mm-wide implants. Conversely, a recent publication suggested that IP reduces implant strength irrespectively of the implant diameter, and that bone-level implants (with lower CIR) will have better outcomes than those with tissue-level design (135). Finally, the grade of the titanium used for implant manufacturing is also of importance as lower grades of titanium have been associated with lower resistance to fracture. Wider implants can be chosen to overcome mechanical challenges in such cases (160).

In our studies, IP allowed to create a smooth and homogenous surface, although some irregularities and polishing defects were observed. Some amount of debris was also detected and generally consists of titanium and polymer particles from the bur coating. A thorough irrigation with saline or a low-abrasive air-powder have been recommended to remove them and avoid inflammatory reactions of the peri-implant tissues (120,161). These findings are likely to be more obvious and frequent in a real clinical scenario due to the limited access and visualization of the surgical area. Indeed, performing IP in the lingual aspect of a lower molar with adjacent teeth is challenging and will probably result in a less homogeneous surface. Further research is required to evaluate which variables affect the final surface roughness after IP.

Most fractures occurred in the platform area of the implants. In fact, all control implants in both experiments fractured in this area, suggesting that the platform of 3.5-mm-wide external hexagon implants is more fragile than its body. Other authors found similar results (136,150) but, when regular platform implants subjected to IP are tested, body fractures have also been observed (120). In the present studies, 6 implant body fractures and 2 prosthetic screw fractures were registered in the IP groups. This clearly shows that IP weakens the implant body.

It is also important to state that fractures appear to be ductile, caused by deformation of the surfaces. Platform fractures occurred on the bending direction of the strength test and a deformation of external hexagon was clearly visible. Indeed, fractures and deformation were clearly visible in all SEM images (Figure 5 of publication 1 and Figure 4 of publication 2).

Even though, the present studies complied with UNE-EN ISO 14801:2016 (third edition) regulation, they have some limitations inherent to the *in vitro* design. All IP procedures were performed in ideal laboratory conditions that may not be present in a real-patient

scenario. Instead of using a milling machine, IP was performed in a free-hand manner. Although this slightly compromises the standardization of the procedure, it has the advantage of increasing the external validity of the results. On the other hand, static compressive loads were performed at a 30° angle, which does not replicate the daily complex oral function of the patients. Moreover, it does not assess mechanical failure by fatigue or stress (39). Future research should employ dynamic testing to draw more reliable conclusions. Besides, the type of implant-supported prosthetics (single/multiple, fixed/removable, with/without intermediate abutments, etc.) should also be evaluated, since mechanical properties will probably be affected by this variable. It is also important to mention that implants in the oral environment are exposed to protein-containing serum, which in turn can favour corrosion and increase the risk of corrosion-fatigue fracture, conversely to our room-air experiment conditions (162). However, no significant differences in fracture strength were found after artificial aging of dental implants (163). Human clenching forces range from 98N to 1243N(55) and are determined by several factors such as age, gender, tooth support or tooth location (56). The top of this range would fracture all implants in the present studies, regardless of their BL, CIRs or being submitted to IP. Implants placed in molars, with high CIRs and/or with important degrees of BL should be assessed carefully as an increased fracture risk is expected. In these situations, IP might increase the risk of mechanical complications. In these particular situations, wider fixtures seem to have more positive results (135,136).

In general, clinicians can consider IP as a safe procedure in 3.5-mm-wide platform implants with external hexagonal connection. On the other hand, high degrees of BL and unfavourable clinical CIRs, which are common findings in implants affected by PI, seem to be more relevant regarding the risk of fractures. So, according to the present results, professionals should base their clinical decisions on the case-specific CIR and BL, rather

than in the IP itself, since this procedure *per se* does not significantly reduce implant strength. It is also important to recommend a thorough clinical and radiological examination of the implant platform for cracks or fissures before engaging in an IP procedure since they can already be present, particularly in cases of advanced BL or unfavourable CIR.

Since there is no long-term data on IP, there is clear need for research is this area. Firstly, it is important to determine the resistance to fracture of new materials used for dental implants, namely different titanium alloys and ceramic materials. Another field that requires future research is whether IP is safe for the treatment of PI in these materials. Although zirconia-based dental implants have shown short-term promising results, titanium dental implants are still dominant due to its proven success and its biological/physical characteristics (28).

In this thesis, only 3.5-mm-wide platform external hexagon titanium implants were used. The impact of different platform diameters and connections designs in the resistance to fracture of implants submitted to IP according to different BL and CIRs should also be addressed in the future. On the other hand, the external validity of our results can also be increased by including different clinical situations. The number of implants, angulation, the type of prosthesis (removable or fixed), the employed prosthetic materials and the use of intermediate abutments should be tested to better understand the mechanical behaviour of the entire implant-abutment-prosthesis complex and improve the clinical decision-making process.

Finally, as mentioned previously, fatigue testing with cyclic loading should be performed, in order to obtain more clinical relevant information.

CONCLUSIONS

Conclusions

1. Implantoplasty does not seem to increase the risk of fracture of 3.5-mm-wide external hexagonal connection implants, regardless of the amount of bone loss and the clinical crown-to-implant ratio. Implantoplasty causes the highest decrease in the mechanical resistance when 2.5:1 crown-to-implant ratios are present, with a mean maximal compression force reduction of 193.54N (95%CI: 11.91N to 375.17N).
2. An unfavorable crown-to-implant ratio leads to a significant reduction of the resistance to fracture of 3.5-mm-wide implants with external hexagonal connection, both with and without implantoplasty. Implants with implantoplasty and 3:1 crown-to-implant ratio have a significant reduction of the maximal compression forces that ranges from 527.09N to 964.41N in comparison with implants with a 2:1 crown-to-implant ratio.
3. Considering total sample mean values, bone loss significantly reduces the resistance to fracture of 3.5-mm-wide implants with external hexagonal connection. Implants with implantoplasty present a mean reduction of the maximal compression forces of 158.43N (95%CI: -5.94N to 322.79N; p= 0.058) when bone loss increases from 3 to 7.5mm.
4. Implantoplasty reduces the thickness of the implant walls between 0.26mm and 0.56mm.
5. The platform is the weakest part of 3.5-mm-wide external-hexagon dental implants when they withstand a compression load at 30° from the vertical axis, since 90% of the fractures occur in that area.

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SUPPLEMENTARY FILES

Ethics approval

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Eduard Valmaseda Castellón and Rui Figueiredo, as codirectors of the thesis project: "Mechanical resistance to fracture of narrow platform with external connection dental implants submitted to implantoplasty with different bone levels and crown/implant ratios. An in vitro study.", of the student Bruno Alexandre Morais Leitão de Almeida, declare that: this project does not include any experiment on Humans or animals and that no biological samples of any sort will be used. All interventions will be performed using titanium dental implants fixed on resin blocks.

The authors consulted the Committee for Bioethics of the University of Barcelona who decided that there was no need of ethical appreciation by the Committee and that the present declaration is sufficient.

Barcelona, 04th of May 2017

Eduard Valmaseda Castellón (Director)

Rui Figueiredo (Director)

Bruno Alexandre Morais Leitão de Almeida (Student)

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Effect of crown to implant ratio and implantoplasty on the fracture resistance of narrow dental implants with marginal bone loss. An in vitro study.
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Thank you for submitting your article for our consideration.

Your above referenced article with the following authors: Bruno Leitao-Almeida,Octavi Camps-Font,André Correia,Javier Mir-Mari,Rui Figueiredo,Eduard Valmaseda-Castellón , has been evaluated by the reviewers. We are happy to inform you that they have recommended accepting the manuscript for publication in Medicina Oral Patologia Oral Cirugia Bucal.

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