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ORIGINAL ARTICLE

Fractographic analysis of fractured dental implant components

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Abstract *Background/purpose:* This study investigated in seven patients the main causes of accidental fractures of various implant components.

Materials and methods: We used a scanning electron microscope and transmission electron microscope to observe the fracture interfaces of four fixtures, six abutment screws, and nine gold screws retrieved from patients with prosthetic problems.

Results: In all fixtures and some abutment screws, parafunctional force and a cantilever design ultimately resulted in movement of low-angle grain boundaries (LAGBs) at most fracture surfaces. Fractographic observations showed that overloading deformed the grain sizes, and the no precipitates were present on the high-angle grain boundaries (HAGBs) or matrices of some abutment screws and most gold screws.

Conclusion: To avoid implant fracture, certain underlying mechanical risk factors should be noted such as patients with a habit of bruxism, bridgework with a cantilever design, or two implants installed in a line in the posterior mandible.

Introduction

Since Brånemark introduced the concept of osseointegration, dental implants have been used successfully as

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a treatment option for edentulous patients. Most screw-retained implant restorations consist of five elements: the implant, an abutment core, an abutment screw, a gold cylinder, and a gold screw. Mechanical problems associated with prosthetic treatment involve the interface between the individual implant, the abutment, and the prosthesis. Clinical observations of difficulties and complications involving implant or screw fractures have lately garnered increasing attention.[1—7]

During the past three decades, much basic and clinical research has focused on the associations between implants, microbiota, and occlusal loading. It is believed that major factors that cause implant failures after primary healing and osseointegration are peri-implant infections and/or extensive occlusal stress.[8] Biological implant failures seem to cluster in ways that suggest two different models.[9,10] Early failures occur a few weeks to a few months post-implantation because of tissue damage, excessive bone necrosis, or microbial contamination of the implant during surgery. Late failures arise from pathological processes involving biomechanics and host-parasite interactions.

Implant fracture is a major cause of late prosthetic implant failure. Adell et al reported a 3.5% prevalence rate of implant fracture, with most fractures occurring 5 years after clinical follow-up.[11] For instance, an analysis of 4045 implants used in clinical treatment showed that 0.2% of the implants fractured during a 5-year period.[12] The causes of implant fracture may be summarized in three categories: (1) defects in implant design or material; (2) nonpassive fit of the prosthetic framework; and (3) physiological or biomechanical overload. Cause-effect associations between the oral environment and the mechanical event of fatigue fracture require further investigation.

Following up on the last 20 years (1989 ~ 2010) of clinical periodontics at Taipei Medical University Hospital, we found that most accidental fractures of various implant components (Nobel Biocare, Gothenburg, Sweden) implied certain underlying risk factors that are worth investigating and discussing. In our laboratory we therefore analyzed the main causes of accidental fracture of different implant components and propose an equation to avoid further problems related to the bridge design of implant prostheses.

Materials and methods

Clinical information on patients with different fractured components

We collected and analyzed the full records of patients accepted for implant therapy in the Periodontal Clinic of Taipei Medical University Hospital (Taipei, Taiwan). The study involved 210 implant sites in 170 patients (40.6% were males with an age range of 26—84 years; 59.4% were females with an age range of 20—68 years). All patients committed to a final treatment with a single tooth replacement (55 fixtures), an implant-supported multiple-unit bridge (432 fixtures), or overdenture therapy (68 fixtures). There were seven patients with fracture interfaces consisting of four commercially pure grade I titanium implants, six titanium abutment screws, and nine gold screws retrieved from problematic prostheses. The microstructure of fractured implant components was investigated by using metallographic techniques, which included a scanning electron microscope (SEM) and transmission electron microscope (TEM).

Fractography

We prepared samples by sectioning, mounting, grading, polishing, and wet etching with a 10% nital solution. We used SEM and TEM to analyze the fractography of the fractured metal surface architecture. After ultrasonic cleaning in acetone, we examined the fractured surfaces of the test specimens with a Hitachi S-2400 SEM (Angstrom Scientific Inc., Ramcey, NJ, USA) operated at 20 kV. TEM samples were prepared for electron transparency by mechanical thinning, followed by ion milling in a precision ion polishing system. Specimens were observed using a JOEL 2010 TEM (MIT-CMSE Electron Microscopy Shared Experimental Facility, MA, USA) operated at 20 kV.

Results

Implants with fractured components

Among the 170 patients, the cumulative survival rate of the implants was 99.0% at 10 years and was 82.9% at 15 years. Table 1 depicts the clinical situations in which total implant failure occurred in seven patients (labeled A—G). Two patients (A and F) experienced implant fracture because of a history of bruxism. Three fixtures with a multi-unit implant-supported fixed bridge design (patients A, C, and F) fractured 2—4 years after abutment connection. The implants of patients B and G disintegrated because short implants (7 mm, regular platform/wide platform) were used to support a posterior single-tooth replacement or used as a distal abutment to support an overdenture in the posterior maxillary area. In two patients (C and E), fixtures with an anterior or posterior cantilever design of a two-implant supported bridge either fractured or disintegrated over different periods of time (Table 1).

Four abutment screws fractured because the patients (A, C, E, and F) received bridge work with a cantilever design. Two abutment screws fractured because two patients (D and G) received a design for a single tooth replacement with one implant. Among the 170 patients, we found six gold screws fractured in conjunction with four fractured fixtures (patients A, C, and F), and three gold screws fractured in conjunction with abutment screw fractures (patients D and E).

Fractography of fixtures

The SEM study summary revealed fatigue with striations on most fracture interfaces of fixtures. As demonstrated in the sample obtained from one patient (Fig. 1A, SEM magnification at 20%), the fracture occurred at the junction between the abutment screw and the hollow space in the fixture. The maximum ultimate strength of titanium implants gradually decreased after parafunctional grinding

Table 1 Summary of seven patients with the clinical accident of fractured components in different prosthetic parts.

Patient no.	Gender	No. of failed fixtures	No. of fractured abutment screws	No. of fractured gold screws	Postulated risk factors
A	Male	++, fractured	+	++	Bruxism, 2 implants in posterior mandible
B	Female	+, disintegrated	—	—	Short implant (RP, 7 mm smooth surface), installed in an area of tuberosity
C	Male	+, fractured	+	++	2 units with posterior cantilever pontic at the posterior mandible
D	Male	+, disintegrated	+	+	Bruxism, single-tooth replacement
E	Male	+, disintegrated	+	++	2 units with anterior cantilever pontic in the posterior mandible
F	Male	+, fractured	+	++	Bruxism, 2 implants support 3 units ISFB with anterior pontic design
G	Female	+, disintegrated	+	—	Short implant (WP, 7 mm, Tiunit)

"+" = number of components; "−" = negative finding; RP = regular plateform; ISFB = implant supported fixed bridge; WP = wide plateform.

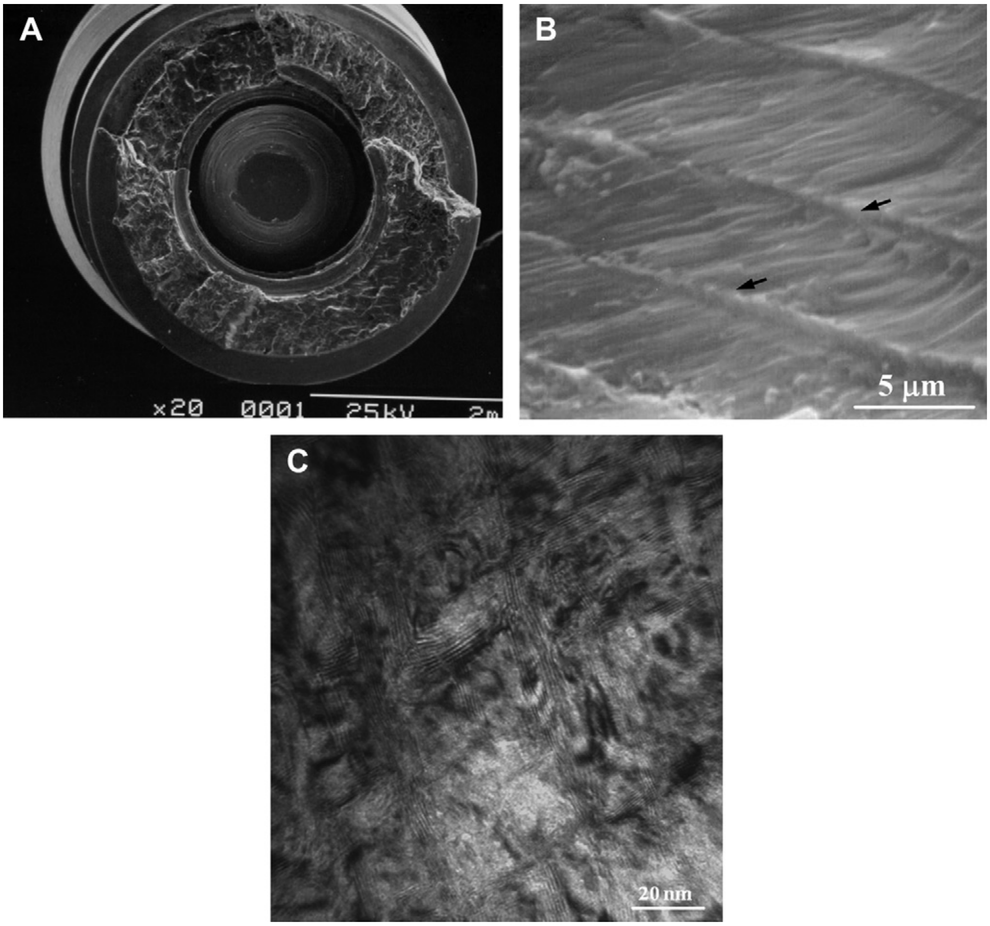

Figure 1 SEM and TEM images of the fractured surface of a titanium-based fixture. (A) Low magnification of the fractured interface of fixture (SEM magnification, 20%). (B) Striations and propagations of slip bands become wider as the occlusal loading persists (SEM magnification, 1000×). The striations are perpendicular to the fatigue crack propagation direction. (C) Parafunctional forces and a cantilever design result in movement of the low-angle grain boundaries (LAGBs) at the fracture surfaces of fixtures (TEM magnification, 30,000×). LAGBs consist of periodic arrangements of crystal dislocations. An external shear stress exerts a force on a single dislocation in a crystal and similarly exerts a force on an ensemble of dislocations. Striations and propagations of slip become wider as loading persists.

(Fig. 1B). As stress increased in a location with fatigue, stress variation resulting from bruxism induced the fatigue striations. This indicates that parafunctional forces and the cantilever design resulted in movement of low-angle grain boundaries (LAGBs) on the fractured surfaces of most fixtures (Fig. 1B). An LAGB is a boundary having a misorientation of less than 11 degrees. Generally speaking, an LAGB is composed of an array of dislocations and its properties and structure is a function of the misorientation. From the TEM analysis, the degree of the grain boundaries in Fig. 1B was approximately 9.5 degrees. Hence, this was categorized as an LAGB. In the same manner that external shear stress exerts force on a single dislocation in a crystal, it also exerts force on an ensemble of dislocations. Striations and propagations of slip bands (shown in Fig. 1C) become wider as loading persists. The results provide evidence of the effect of shear stress on metallic fatigue striations.

Fractography of abutment screws

Most abutment screws exhibited distinctive primary fractured interfaces with striations and a dimpled appearance (Fig. 2B). When there was occlusal overloading, a transcrystallized fracture was easily visible. Grain sizes were deformed, and we found no precipitates on the grain boundaries or the matrix (Fig. 2B). We also observed clear dislocation loops in the fractured interfaces of the abutment matrix that was induced by external shear stress (Fig. 2C). Brittle fractures and fatigue striations occurred in the same fractured abutment screws.

Fractography of gold screws

In the gold screw groups (Fig. 3B), we observed dimpled patterns in all samples. Dimpled sites (denoted by the arrow in Fig. 3B) revealed ductile fractures in the fractured surface of gold screws. However, grain boundaries were driven by the stored energy of the stress variation (which may have been caused by sudden tensile stress), thereby inducing recrystallization and boundary curvature (i.e., grain growth). Grain boundary motion of the gold alloys was confined to high-angle grain boundaries (HAGBs). Compared to the LAGBs in Fig. 1B, the properties of HAGBs are normally independent of misorientation. The misorientation in HAGBs is greater than approximately 11 degrees. (The

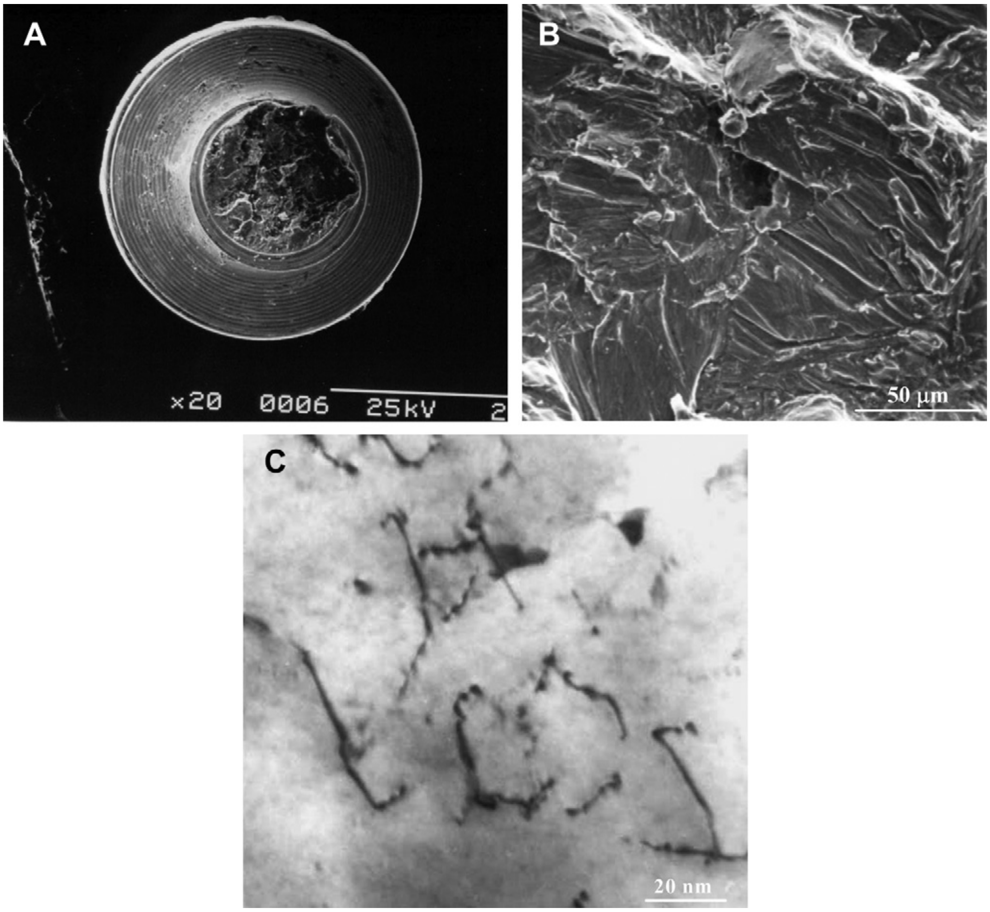

Figure 2 SEM and TEM images of an abutment screw after fracture. (A) Low magnification of the fractured surface of abutment screw at the narrowing neck area (SEM magnification, 20×). (B) Fractographic analysis shows that as the loading increases, grain sizes are deformed; there are no precipitates on the grain boundaries or matrix of most abutment screws (SEM magnification, 1000×). (C) Dislocations exist in the grain boundaries and the matrix of the abutment screws after load stressing (TEM magnification, 30,000×).

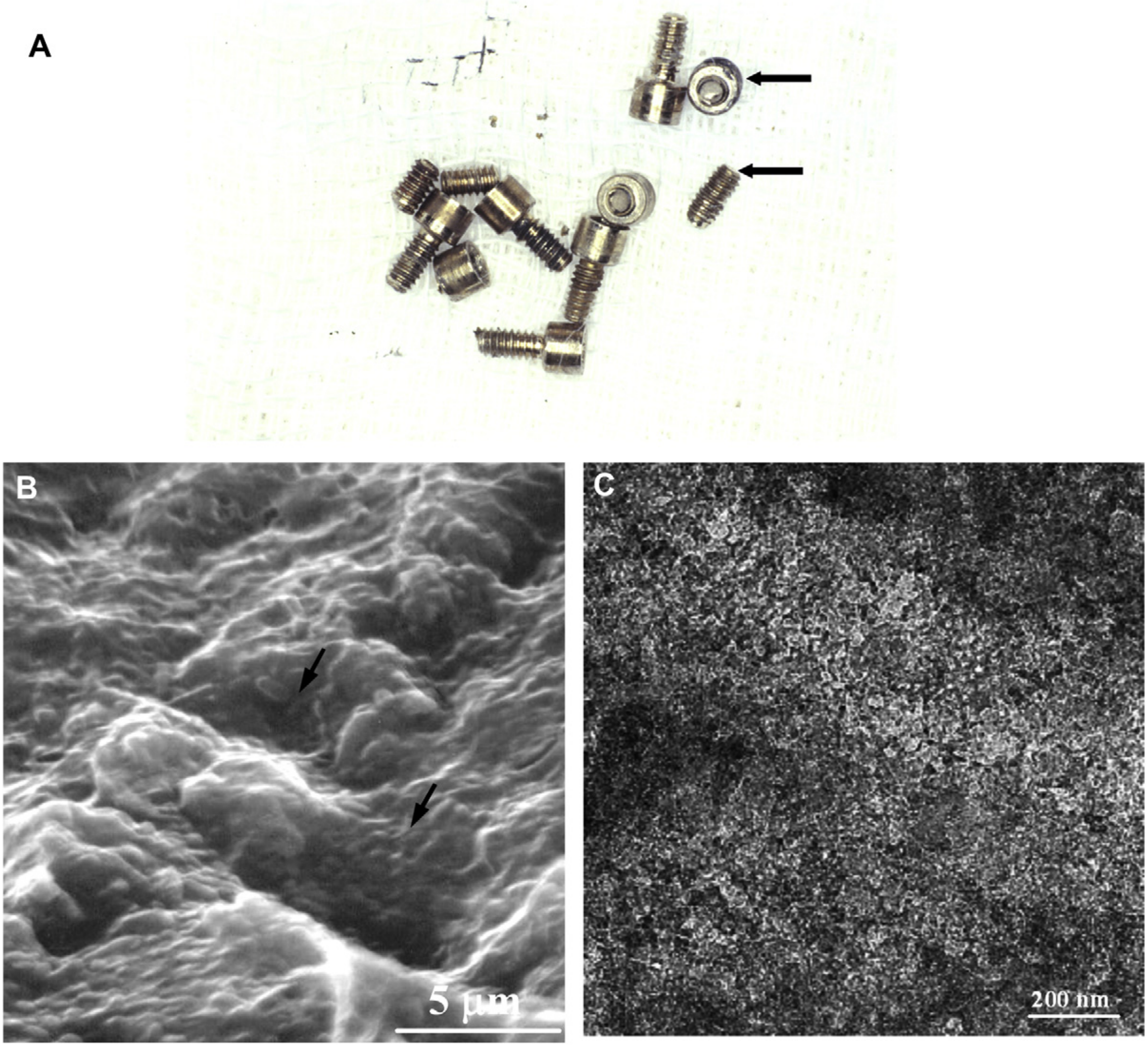

Figure 3 SEM and TEM images of the fractured surface of a gold screw. (A) Two pieces of fractured fragments of one gold screw are present (black arrows). The fractures occurred in the shank area for most of the screws, except for the one screw at the bottom of the picture. (B) Dimpled microstructures are present on the fractured surface of a gold screw (SEM magnification, 1000×). (C) Grain boundary motion was confined to high-angle grain boundaries (HAGBs) in both fractured screw components with a dimpled appearance. Based on TEM analysis, the degree of the grain boundaries is approximately 13.3 degrees. (TEM magnification, 30,000×).

transition angle varies from 10 to 15 degrees, depending on the material.) Using TEM analysis, we determined that the grain boundaries in Fig. 3B were approximately 13.3 degrees. Thus, we classified it as an HAGB. Moreover, micro-dimpled surfaces could be easily observed in the TEM image (Fig. 3C).

Discussion

This SEM study of the fractured architecture of four fixtures showed the presence of slip and fatigue striations, which produced a cracked front under cyclic loading. It illustrates typical fatigue striations with secondary crack formation since the striations were perpendicular to the fatigue crack propagation direction.[16] An SEM examination of clinical specimens revealed that most fractured surfaces of fixture components had striations that were similar to the striations occurring in laboratory-fatigued specimens (unlike the dimpled surfaces of overloaded specimens).[17] Piattelli et al also presented a light and scanning electron microscopic report of four fractured implants in two patients.[18] Both patients had a history of bruxism, hypertrophic masticatory muscles, and wear on occlusal surfaces. We surmise that shear stress induced by an inadequate biomechanical prosthetic design accounted for most of the fatigue failures of fixtures and abutment screws. In addition, the fundamental differences between natural teeth and implants may point to rigorous occlusal control as a key factor in the success of implant-supported prostheses. The absence of periodontal ligaments may lead to occlusal overload and implant failure because of the inability to adjust the intensity and axial transmission of momentum from the occlusal force and because of the absence of periodontal proprioceptors.[19]

Rangert et al proposed a checklist to evaluate deleterious load factors for posterior partial prostheses.[20] Risk factors affecting the geometric support capacity of prostheses were the number and position of implants, implants placed in a line, and a prosthesis with a cantilever design. For treatment purposes, a history of bruxism was also categorized as an occlusal risk factor. In our report, four fixtures and six abutment screws failed because the patients had received a prosthetic with a cantilever design, two implants were installed in a line in the posterior mandible, or the patient had a parafunctional habit. This shows that microstructural variations such as dislocations (Fig. 2C) are driven by the combination of high cyclic parafunctional forces and lateral bending contacts. LAGBs reflect the low ductile character of titanium implants responding to horizontal shear strength.

The aforementioned fractographic microstructure investigations demonstrate the various stress loads (Fig. 4) that are applied to dental implants after they are subjected to compound stresses ($\sigma_{\text{total stress}}$). According to the resultant force principle, the actual impact equations for bridge design in implant prostheses could be obtained, as follows: $\sigma_{\text{total stress}} = \sqrt{\tau^2_{\text{t(shear stress)}} + \sigma^2_{\text{t(total normal stress)}}}$; $\tau_{\text{t(shear stress)}} = \frac{P_{//}}{A}$; $\sigma_{\text{t(total normal stress)}} = \frac{P_{\perp}}{A} + \frac{Mx}{I}$ (Fig. 4). The fractography in Figs. 1—3 indicates that the fixtures and abutment screws were subjected to fatigue-loading-induced compound stresses ($\sigma_{\text{total stress}}$). Therefore, the horizontal occlusal force induced by lateral excursion contact of the occlusal scheme or induced by high-frequency grinding of a parafunctional habit (Fig. 4) was a major component in $\sigma_{\text{total stress}}$. It was significant that most fractured abutment screws had a combination of transcrystal propagation of fatigue cracks and an overloaded dimpled appearance at the same interfaces. However, in gold screw samples, most fracture surfaces were dimpled with grain boundaries driven by a gradient of occlusal energy that induced normal stresses across the boundary. With increasing periods of normal stress ($\sigma_{\text{t (total normal stress)}}$), the grain boundaries were driven by a gradient of occlusal forces across them. This gradient may have been provided by the stored energy of stress variation such as an overloaded framework design (e.g., the cantilever design, which induces recrystallization and boundary curvature [i.e., grain growth]). Grain boundary motion of the gold alloy was confined to HAGBs. Since they show a continuous perturbation of the perfect crystal in which dislocations lose their identification and completely release their stress in the boundary field, we conjectured that fatigue loading was insufficient to cause the formation of microdefects in gold screws during short periods of normal stress. It is conceivable that normal vertical stresses play a major role in the continuous compound stress that cause HAGBs and gold screw fractures. In addition, bruxism and lateral excursion contacts of the occlusal scheme may also have induced bending, and introduced a normal stress effect on the gold screw components of the adjacent dental implant remote from the inertia of the loaded implant. On the fractography of

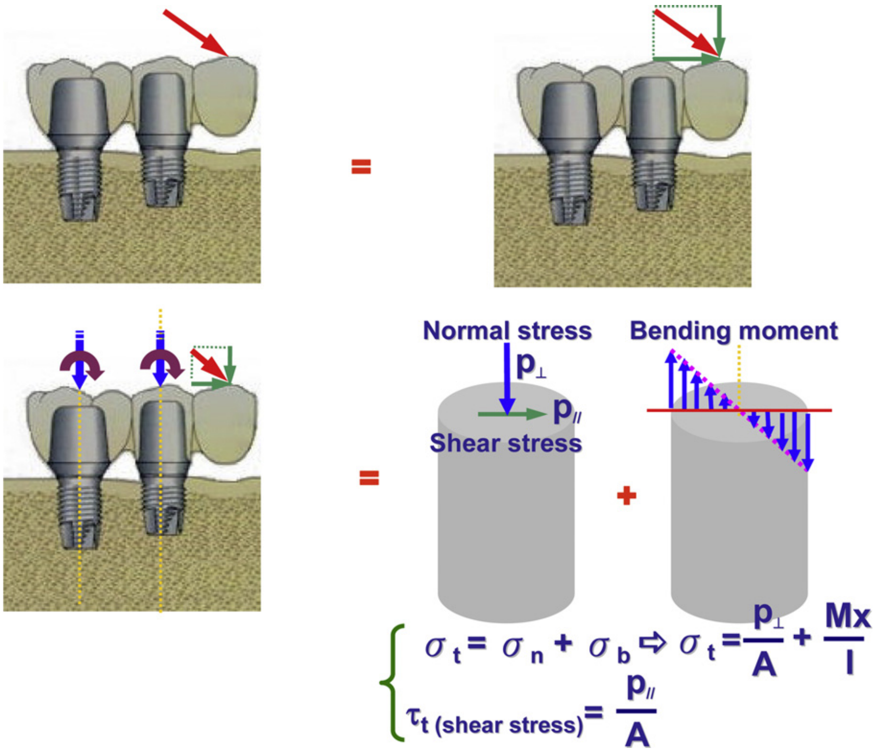

Figure 4 The proposed equation where $P_{//}$ is the horizontal component of occlusal force, $P_{\perp}$ is the vertical component of occlusal force, A is the reaction area, M is the bending moment induced by occlusal force, I is the inertia of the dental implant, and x is the arm of the cantilever.

the gold screws, this phenomenon is clearly demonstrated by dimpling and by microvoids. It also corroborates the design rationale of gold screws: they are a fail-safe mechanism to protect the fixture.

Implant failures that occur after osseointegration has taken place are believed to be related to either bacterial infections or occlusal overloads.[8] In a 10-year prospective study of the association between periodontal and peri-implant conditions, marginal bone levels in 10-year implants were significantly associated with smoking, general health condition, implant location, full-mouth probing attachment level, and changes over time in the full-mouth probing pocket depth.[13] These results indicate an association between periodontal and peri-implant conditions. These tissues change over 10 years in partially edentulous patients. The relationship between periodontitis and peri-implantitis nevertheless remains a matter of debate. Our long-term follow-up showed that none of the implants failed because of plaque-induced peri-implantitis. Most peri-implant inflammations occurring in conjunction with bone loss in our patients was evident around failing fixtures having fatigue cracks that propagated across the implant bodies. Peri-implant inflammation may have lasted as long as 2—4 years until the implant body completely fractured. This clinical evidence is supported by a study using experimental monkey models in which none of the implants with plaque accumulation lost osseointegration.[14] This finding is also supported by a clinical study by Quirynen et al that found that none of the implants with plaque accumulation lost osseointegration.[15]

Our findings revealed that parafunctional forces and the cantilever design resulted in striations and propagation of slip bands at most fracture surfaces of the fixtures (Table 1). The combination of slip fractures and dimple fractography in fractured abutment screws indicated that the awkward position of this component resulted in fatigue stress and overload. Furthermore, fractured screw components with a dimpled appearance occurred in most gold screws in which the multiaxial normal forces were overloaded. This implies that underlying geometric and occlusal control issues should be clinically avoided. This includes patients with a habit of bruxism, a cantilever design for bridgework, or two implants installed in a line in the posterior mandible.

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