Evaluation of Loading Conditions on Fatigue-Failed Implants by Fracture Surface Analysis

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Purpose: *The goal of this study was to determine the relationship between fracture surface morphology and applied stress level for dental abutment screws loaded in cyclic fatigue. If a correlation between fracture surface and load level can be determined, then the fracture surface analysis could be used as a tool to assess the mechanism by which a screw failed and the magnitude of the load at which it failed.* ***Materials and Methods:*** *Test implants were loaded with static and cyclic forces. In the cyclic test, the load versus the number of cycles was plotted as a curve for biomechanical analysis. The fracture surfaces of the failed screws were observed and recorded using scanning electron microscopy (SEM).* ***Results:*** *Two fracture phases, a smooth region and a rough region, were observed on the fracture surface. After identifying the boundary between the 2 regions, the smooth region ratio (SRR), the ratio of the smooth phase area to the area of the whole fracture surface, was measured using digitized SEM images. The mean SRRs were 0.60 ± 0.03, 0.66 ± 0.03, and 0.75 ± 0.03 when the tested implants were subjected to dynamic loading of 60%, 55%, and 50% ultimate failure loading (UFL), respectively. Linear relationships were found between the SRR values and loading magnitude and between SSR and number of cycles.* ***Discussion:*** *The smooth area on the fracture surface can be used to assess the load conditions and internal stress of fatigue-fractured implants.* ***Conclusions:*** *These results demonstrate that fracture surface analysis of fractured implants has the potential to become a useful indicator for assessing implant fracture mechanisms.* Int J Oral Maxillofac Implants 2005;20:854–859

Key words: *dental implants, fatigue, finite element analysis, implant fractures, scanning electron micrography*

Clinical observations have indicated that the major causes of implant failure are *(1)* uncompleted osseointegration, *(2)* complications of the neighboring soft tissues, and *(3)* problems of biomechanics. Among the biomechanical problems, screw loosening and fatigue fracture are major issues.[1,2] Many studies have reported that "screw fracture" is the most common failure mode of implant failure.[3,4] Antheunis and associates[5] commented that occlusal forces, fatigue character, yielding strength of materials, stress relaxation, vibration, and damping effect were all possible causes of screw loosening or fracture.[5] Although many studies have focused on improvement of surgical procedures and of the biomechanical designs of implants,[5,6] implant failures caused by individual chewing habits have seldom been discussed. In some cases, failure to consider this issue could lead to the failure of replacement implants. Until now, an effective method for practitioners to evaluate the loading conditions, such as loading magnitude and loading cycles, to which a fractured implant had been subjected has been unavailable.

Fatigue breakdown, the most common fracture mode of implant screws, can be explained as a prop-

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agation of microscopic cracks caused by stress concentration in a structure. Although fatigue tests on implants have been conducted by several scholars to evaluate whether fatigue limit was affected by different dental implant systems or prosthetic occlusal table sizes,[4,7–9] relationships between fracture surface characteristics and loading conditions have not been discussed.

Fracture surface analysis can be used to infer the failure mechanism of a mechanically loaded structure. In fracture surface analyses, stress values are calculated by quantitating the smooth and rough phases of the fracture surfaces. This technique has been adopted for quantitative analysis of dental ceramics and other dental materials.[10–16]

The goal of this study was to determine the relationship between fracture surface morphology and applied stress level for dental abutment screws loaded in cyclic fatigue. If a correlation between fracture surface and load level can be determined, then the fracture surface analysis could be used as a tool to assess the mechanism by which a screw failed and the magnitude of the load at which it failed.

MATERIALS AND METHODS

Pure titanium implants were tested in this study. The unit consisted of a 10-mm implant with an outer diameter of 3.75 mm (BTO-if-pt-3810; BioTech One, Taipei, Taiwan), a cylindric abutment with a height of 8 mm (BTO-ac-pt-1004; BioTech One), and an abutment screw (BTO-as-st-3810; BioTech One) to connect the components.

To test the bending strength of the samples, static loading tests were performed before the cyclic tests. To apply a static load to the tested implants, and to fix specimens to the testing machine, a custom-designed holding stage of high-strength steel was prepared. To make the specimen holder, a cut was made in a block of the steel at an angle of 30 degrees. To fix the test implant, a hole with internal threads was pre-tapped on the cut surface of the holder. According to the testing protocol of previous studies,[10,17] the implant was locked into the holes up to the second thread from the head of the implant by a torque force of 20 Ncm. Then, cylindric abutments were connected to the implant using abutment screws and tightened to 20 Ncm with a clinical torque driver[18] (Dynamometric Contra-Angle, Ref 2540; Anthogyr, Sallanches, France). Before mechanical testing, the holding device with the test sample was rigidly fixed to the baseplate of the material testing system (858 MiniBionix Axial Torsional Test System; MTS System, Minneapolis, MN). As shown in Fig 1, the test implants were 30 degrees off-axis to produce a clinically relevant bending force.[7,8] Once the implants were fixed and aligned in the machine, a preload was directly applied to the implant under displacement control mode. It caused the tested implant to be displaced 2 mm in a vertical direction. During static testing, vertical load was applied at a rate of 0.05 mm/s until the sample fractured or vertical plastic deformation greater than 2 mm occurred. Five specimens were tested, and for each, the maximum applied load and the mode of failure were recorded. The average value of maximum applied load to cause each tested sample to fail was defined as "ultimate failure loading" (UFL) in this study.

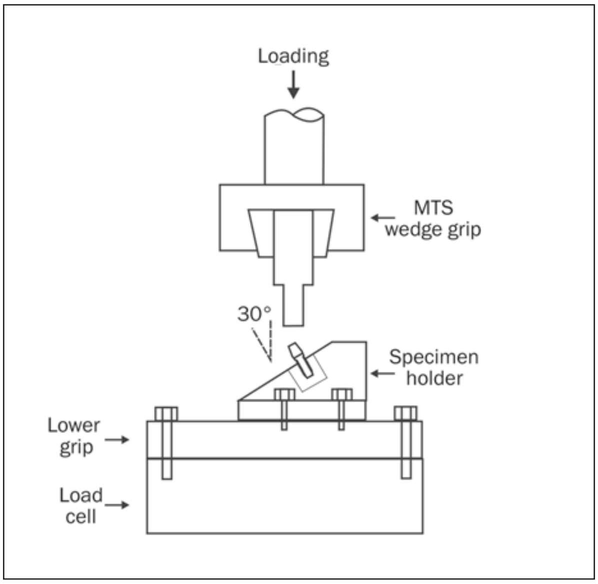


Fig 1 Schematic of test setup.

To produce fatigue fracture samples for fracture surface analysis, a cyclic load was applied to the specimens. The instrument setup and sample fixation were the same as for the static loading test. To minimize vibration of the test machine, and because titanium is a strain rate–insensitive material, the applied cyclic load was set as a sinusoidal force[17] with a frequency of 15 Hz. The load was directly applied to the tested implants under a loading control mode with a minimum to maximum loading ratio[17] of 0.1. The test machine was set to automatically shut off when the specimen failed or the cyclic loading reached 5×10^6 cycles. Seven load magnitudes (90%, 80%, 70%, 60%, 55%, 50%, and 40% mean UFL) were used; 5 specimens were tested at each load magnitude to calculate mean UFL value and standard deviation (SD), for a total of 35 specimens. After each test, the number of load cycles and the mode of failure were recorded. The applied loads (L) were plotted on a

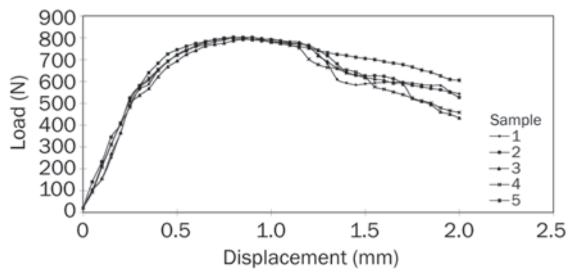


Fig 2 Load-displacement curves of static tests.

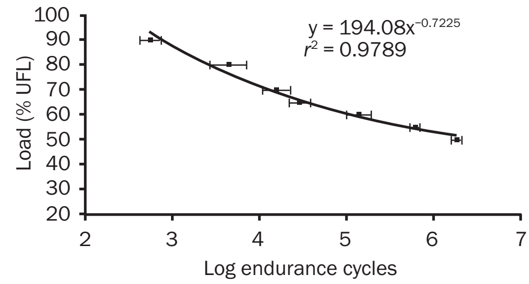


Fig 3 Load versus logarithmic number of cycles in dynamic fatigue testing. Bars show SD from the mean.

graph against the mean cycle numbers (N) for each loading condition to obtain an L-N curve.

The fatigue-fracture surface of the tested implant components was gold-sputtered and examined using a scanning electron microscope (SEM) (S-2400; Hitachi, Tokyo, Japan) at a 15 kV acceleration potential. SEM photographs were taken at 50× and 200× magnification for image analysis. After the SEM photographs were digitalized, the smooth-rough boundaries on the fracture surfaces were identified. Both the areas of smooth region and the whole fracture surface were measured using image analysis software (Image Pro Plus; Media Cybernetics, Silver Spring, MD). In this study, the smooth region ratio (SRR) was defined as the ratio of the smooth phase area to the area of the whole fracture surface. The difference on SRR values between each load group was tested statistically using 1-way analysis of variance. The quantitative relationships between SRR and the fracture parameters, including load and number of cycles, were plotted and compared.

RESULTS

Figure 2 demonstrates the results of static testing. The mean UFL value of the tested specimen was 798.8 ± 4.1 N. The failure mode of static testing was bending deformation at the interface between the stem and first thread of the abutment screw.

The L-N curve obtained from the cyclic-loading test is shown in Fig 3. When the applied load was larger than 60% UFL, bending deformation of the abutment screw was the most common failure mode. Only 1 sample fractured with an applied load of 65% UFL. When the load applied was between 60% UFL and 50% UFL, all of the tested specimens fractured at the abutment screw. When the applied load was smaller than 50% UFL, no significant damage was found in the implant systems after 5 million cycles. Because major fatigue fracture occurred at the applied load of 50% to 60% UFL, only the implants in these load groups were used for later fracture surface analysis.

Typical SEM images of a fractured abutment screw is shown in Fig 4. Smooth and rough surfaces can be seen at the tension and compression sites, respectively. A significant boundary between the smooth and rough regions is shown on the fracture surface. The direction of crack propagation can be identified from the lines parallel to the dimpled lines in the smooth region. Figure 5 contains some sample SEM images of the fracture surfaces of the specimens subjected to 60%, 55%, and 50% UFL. The mean SRR values of these 3 load groups were 0.60 ± 0.03, 0.66 ± 0.03, and 0.75 ± 0.03, respectively. These values increased significantly when the applied load was lowered ($P < .01$).

The relationship between SRR and load magnitude was plotted on the graph shown in Fig 6a; the relationship between SRR and number of cycles was plotted in the graph shown in Fig 6b. Linear relationships were found between the SRR and the 2 parameters. The SRR values decreased when the loading magnitude was lowered (Fig 6a). In contrast, the SRR values increased as the number of cycles increased (Fig 6b).

DISCUSSION

Static testing showed that the failure mode for all 5 tested implants was plastic deformation of the abutment screw. This result is consistent with the findings

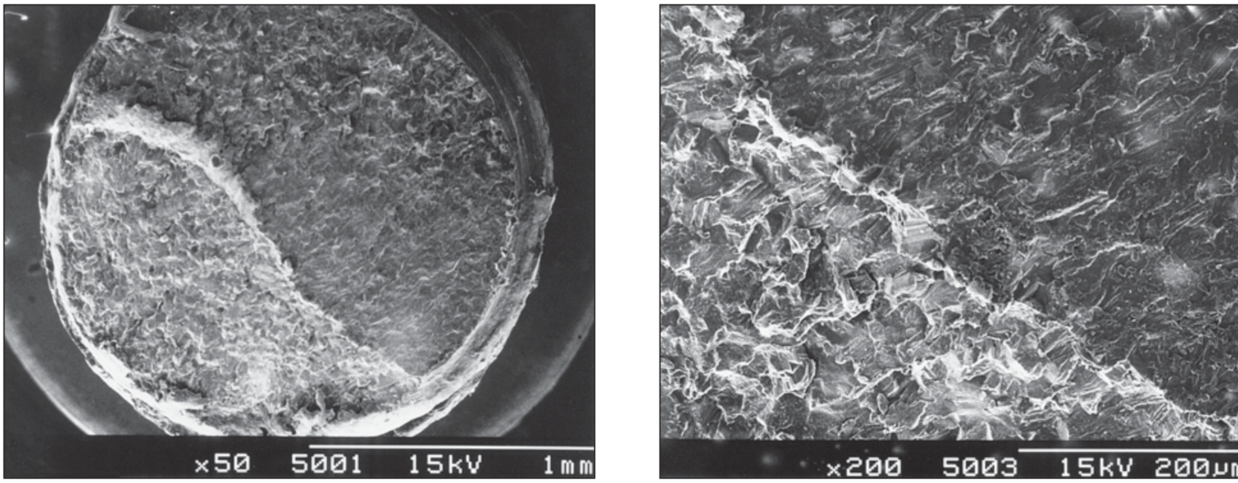
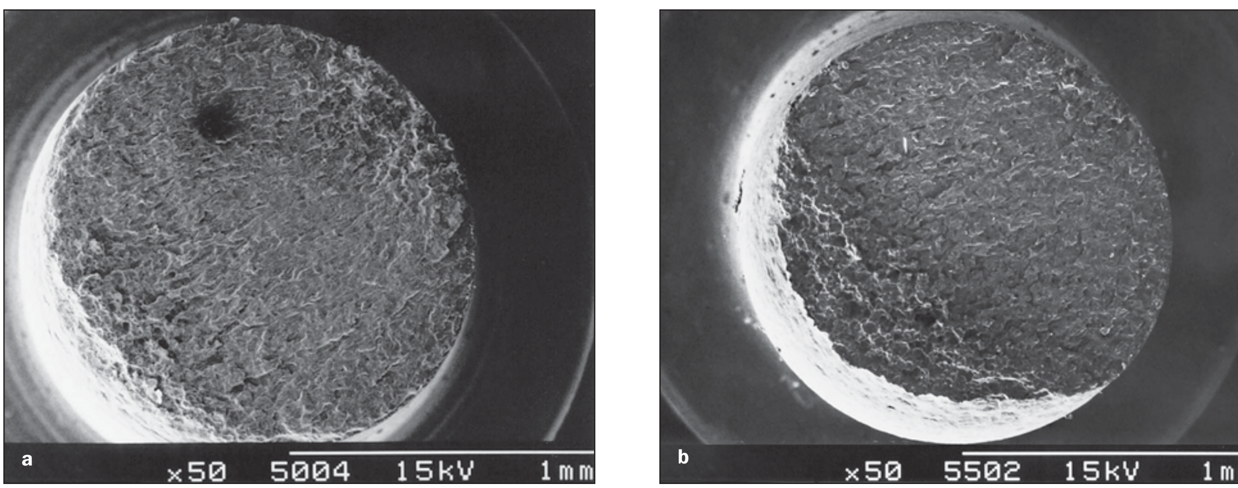


Fig 4 Typical scanning electron photomicrographs from the fracture surface of a failed abutment screw. The boundary can be seen between smooth (upper right) and rough surfaces (lower left) (original magnification ×50 *[left]* and ×200 *[right]*).



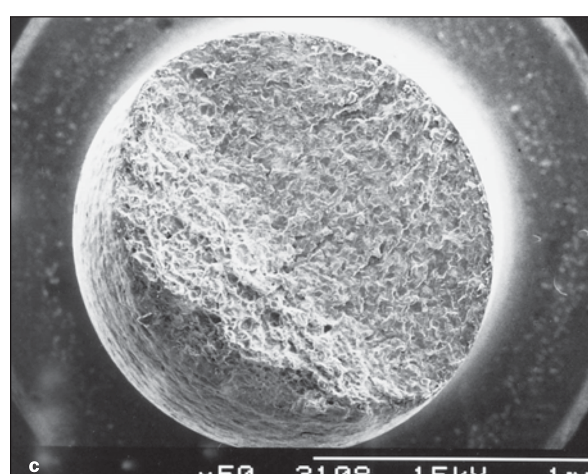
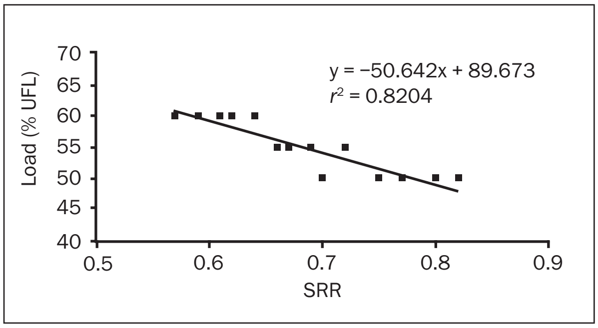


Fig 5 Scanning electron photomicrographs from the fractured surface of failed abutment screws subjected to loads of *(a)* 50%, *(b)* 60%, and *(c)* 70% UFL (original magnification ×50).

of Boggan and coworkers.[9] When the applied force was larger than 514.2 N, the average slopes of the 5 static experimental curves soon decreased (Fig 2). That is, when the tested implant systems were subjected to loads reaching 65% UFL (518.7 N), the systems entered the plastic deformation region. In contrast, abutment screws could be subjected to a repeated force without breakdown if the magnitude of the force was in the elastic region. In Fig 3, when the cyclic load applied to the tested implants was



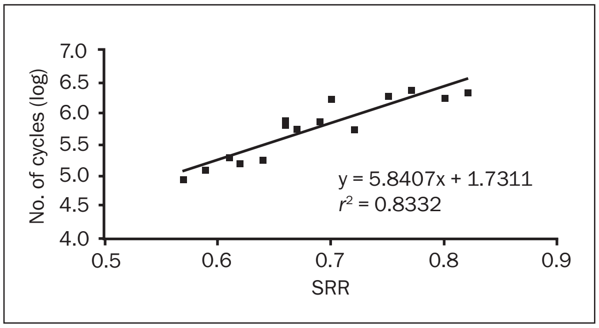


Fig 6 Relationships between SRR and *(a)* applied loading and *(b)* number of cycles are shown.

larger than 65% UFL (518.7 N), the major failure mode of the implants was also plastic deformation on the abutment screw. Therefore, the final deformation was the result of accumulation by each cycle.

Typical maximum bite force magnitude exhibited by adults is 710 N (between premolar and molar; 789 N for men and 596 N for women).[19] Gibbs and colleagues measured the occlusal force during chewing and swallowing and found that the maximum force applied at the cusp is 40% of the maximum bite force.[20] Therefore, the average force applied at the cusp is calculated to be 242 N. In this study, when the applied load was lower than 45% UFL, ie, 360 N, the tested implant system could withstand a minimum of 5 million cycles without significant damage to the components. The average individual chews 2,700 times per day. This amounts to roughly 10 million times per year. Because not every chewing cycle is "active," the chewing cycles previously calculated should be decreased by a factor[21] ranging from 5 to 20. Thus, the maximum of 5×10^6 testing cycles set in this study approximated 25 years of intraoral usage. Therefore, in fatigue analysis, the tests were considered to have been successfully completed if the implant survived up to 5×10^6 loading cycles.[22]

The lower the applied force, the greater the number of fatigue cycles sustained by the specimens (Fig 3). Although the curve flattened as the load decreased, the flat point, ie, the endurance limit, cannot be identified in Fig 3. It was not the major intent of this study to produce an endurance curve for the tested implant system but rather to produce and examine fractured surfaces under fatigue conditions. Thus, as reported in the study of Morgan and coworkers,[17] the number of cycles to failure was not considered critical in this study. In fact, some metals do not demonstrate a significant flat point, and the fatigue parameters cannot be cycled indefinitely.[21]

Fatigue fracture has been explained as propagation of microscopic cracks caused by stress concentration in structural analysis. The science of fracture surface analysis is firmly established as a means of failure analysis in the field of engineering. However, the use of quantitative fractography in dental materials research has been a subject of little interest,[11] especially for dental implant applications.

During the fracture process, stress concentrates at the tips of the cracks, thus accelerating the speed of propagation. Finally, the material fractures as the concentrated stress surpasses its limitation. As the microcracks start, initially, the velocity of crack propagation is slow, and a smoother surface can be identified, representing the surface of the fatigue fracture. While the repeated load continues, the stable fracture process is followed by an unstable fracture stage, resulting in the final breakdown of the abutment screw.[15,23] Therefore, the smooth area on the fracture surface can be used to assess the load conditions of fatigue-fractured implants. As shown in Fig 4, significant boundaries between the smooth and rough regions were clearly found on the surfaces of fractured abutment screws. When the SRR values of the fractured screws obtained from these fatigue tests were plotted against their load magnitudes and number of cycles, linear relationships with high correlation coefficients were obtained for each plot in Fig 6. These results indicate that load conditions, such as load magnitude and number of cycles that a fractured screw sustains, can be evaluated quantitatively by measuring the implant's SRR values.

For an implant, loading angle is also an important parameter in fracture analysis. The stress distributions in implants could be changed as a result of alteration of the loading angle. Therefore, specific relationships between loading angles and an implant's SRR values should exist. A conclusion about the relationship between loading angles and an implant's SRR values cannot be drawn from the present study; this is a subject for future investigation.

In summary, the present results demonstrated that fracture surface analysis has the potential to become a useful tool for assessing dental implant fracture mechanisms. The method presented in this study can serve as a reference for future advanced in vivo studies.

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