Mechanical Testing of Implant-Supported Anterior Crowns with Different Implant/Abutment Connections

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Purpose: This study evaluated the reliability and failure modes of anterior implants with internal-hexagon (IH), external-hexagon (EH), or Morse taper (MT) implant-abutment interface designs. The postulated hypothesis was that the different implant-abutment connections would result in different reliability and failure modes when subjected to step-stress accelerated life testing (SSALT) in water. Materials and Methods: Sixty-three dental implants (4 × 10 mm) were divided into three groups (n = 21 each) according to connection type: EH, IH, or MT. Commercially pure titanium abutments were screwed to the implants, and standardized maxillary central incisor metallic crowns were cemented and subjected to SSALT in water. The probability of failure versus number of cycles (95% two-sided confidence intervals) was calculated and plotted using a power-law relationship for damage accumulation. Reliability for a mission of 50,000 cycles at 150 N (90% two-sided confidence intervals) was calculated. Polarized-light and scanning electron microscopes were used for failure analyses. Results: The beta values (confidence intervals) derived from use-level probability Weibull calculation were 3.34 (2.22 to 5.00), 1.72 (1.14 to 2.58), and 1.05 (0.60 to 1.83) for groups EH, IH, and MT, respectively, indicating that fatigue was an accelerating factor for all groups. Reliability was significantly different between groups: 99% for MT, 96% for IH, and 31% for EH. Failure modes differed; EH presented abutment screw fracture, IH showed abutment screw and implant fractures, and MT displayed abutment and abutment screw bending or fracture. Conclusions: The postulated hypothesis that different implant-abutment connections to support anterior single-unit replacements would result in different reliability and failure modes when subjected to SSALT was accepted. Int J Oral Maxillofac Implants 2013;28:103–108. doi: 10.11607/jomi.2443

Key words: cementation, dental implants, fractography, implant-supported prostheses, reliability, step-stress accelerated life testing

Single-tooth replacement involving osseointegrated implants is among the most popular and successful treatment options, presenting 89.4% estimated survival rates after 10 years in function.1 However, despite the high success rates reported for dental implant treatment,2 mechanical complications in the prosthetic components, such as loosening and/or fracture of the abutment screws, have been reported and remain under investigation.3–5 Once osseointegration has been achieved and maintained, the stability of the implant-abutment connection becomes a key factor for the success of the restoration, especially in single-tooth replacements, where the incidence of mechanical complications is highest.5 Therefore, failures should be explored to gain insight into the mechanical behavior of different implant-abutment connection configurations, since they may compromise function and quality of life.7,8

From a biomechanical point of view, one major concern among different implant-abutment connection designs is the external force exerted on components via oral function, which is concentrated mainly on the abutment screw, especially in external-hexagon (EH) connections.9,10 In contrast, internal-hexagon (IH) connections have been claimed to be more mechanically
stable, since the load is distributed deep within the implant, where engagement with a long internal wall shields the abutment screw.\textsuperscript{10–12} High rates of mechanical complications (6\% to 48\%) have been reported for EH implants,\textsuperscript{13–15} whereas fewer episodes of abutment loosening (3.6\% to 5.3\%) seem to occur in Morse taper (MT) connections.\textsuperscript{16}

The maintenance and stability of screw-type connections are challenged by forces exceeding that of the torqued abutment/crown system.\textsuperscript{17} However, lower physiologic forces, applied repeatedly, although they do not necessarily surpass the failure threshold of the assembly, may potentially lead to gradual loosening of the implant-abutment connection and/or failure as a result of fatigue.\textsuperscript{5,18,19} The ensuing misfit of a loose abutment connected to an implant may not only impose taxing stresses in the crestal bone, potentially leading to resorption,\textsuperscript{20,21} but it may also serve as a bacterial reservoir, contributing to peri-implant tissue inflammation.\textsuperscript{22}

Laboratory fatigue studies have shown improved mechanical behavior for prostheses supported by implants with an internal connection versus implants with external connections.\textsuperscript{5,23} A specific evaluation comparing EH and IH connections to MT connections was performed in a finite element investigation; the results showed the lowest stress concentration in the abutment screw of the MT connection.\textsuperscript{10} Whereas that study provided insight about the stress concentrations of different implant/abutment configurations, the clinical significance of the presence of stresses per se requires further validation by mechanical testing, such as fatigue. Because comparisons have frequently been made between different implant systems comprising different implant geometry, an evaluation of the mechanical behavior and failure patterns of EH, IH, and MT connections within the same implant system is warranted.

The aim of this study was to evaluate the reliability and failure modes of implant-supported anterior crowns restored with different implant connections (IH, EH, and MT). The postulated hypothesis was that different implant connections used as anterior single-unit replacements would show different rates of reliability and different failure modes when subjected to step-stress accelerated life testing (SSALT).

**MATERIALS AND METHODS**

**Sample Preparation**

Sixty-three commercially pure titanium dental implants (4 mm in diameter, 10 mm in length, Emfils, Colosso Evolution System) were divided into three groups (n = 21) according to the implant/abutment connection design: EH (HEE Evolution; Fig 1a), IH (ECI Evolution; Fig 1b), and MT (Fig 1c). All implants were vertically embedded in acrylic resin (Orthoresin, Degudent) that had been poured into a 25-mm-diameter plastic tube. The top platform was left at the level of the resin surface.

A maxillary central incisor crown was waxed into an anatomical shape and cast in cobalt-chromium alloy (BEGO). To reproduce the anatomy of the crowns, an impression was taken from the first waxed pattern and used by the technician as a guide during waxing of the remaining crowns. The respective prefabricated abutments (commercially pure titanium; Emfils, Colosso Evolution System) were tightened with a torque gauge according to the manufacturer’s instructions (30 Ncm) using titanium alloy abutment screws (titanium-aluminum-vanadium). Following connection of the corresponding abutments to the implants, the cementation surface of the crowns was blasted with aluminum oxide (particle size \( \leq 40 \mu m \); 276 KPa of compressed air pressure), cleaned with ethanol, dried with air free of water and oil, and then cemented (RelyX Unicem, 3M ESPE).
Mechanical Testing and Reliability Analysis
For mechanical testing, the specimens were subjected to 30-degree off-axis loading. Three specimens of each group underwent single-load-to-failure (SLF) testing at a crosshead speed of 1 mm/min in a universal testing machine (INSTRON 5666); a flat tungsten carbide indenter was used to apply the load at the incisal edge of the crown. Based upon the mean values from SLF testing, three SSALT profiles were determined for the remaining 18 specimens of each group, which were assigned to mild (n = 9), moderate (n = 6), or aggressive (n = 3) fatigue profiles (ratio 3:2:1, respectively).24–26 These profiles were named based on the stepwise load increase by which they were fatigued along the cycles. Hence, in the mild profile, a specimen was cycled longer to reach the same load level as that allocated in the moderate profile and even longer in the aggressive profile. The data collected during testing at different stress profile levels were used to estimate the parameter that best fit the data by means of commonly used life distributions, such as log normal, exponential, or Weibull.

The prescribed fatigue method was SSALT under water at 9 Hz with a servo–all-electric system (Test-Resources 800L); the indenter contacted the incisal edge, applied the prescribed load within the step profile, and lifted off the incisal edge. Fatigue testing was performed until failure (bending or fracture of the fixture screw and/or bending, partial fracture, or total fracture of the abutment) or survival (no failure at the end of step-stress profiles, where maximum loads were up to 600 N).27–29

Use-level probability Weibull curves (probability of failure versus number of cycles) with a power law relationship for damage accumulation were calculated (Alta Pro 7, Reliasoft).30 Reliability (the probability of an item functioning for a given amount of time without failure) for completion of a mission of 50,000 cycles at a load of 150 N showed that the cumulative damage from loads reaching 150 N would lead to implant-supported restoration survival of only 31% of EH assemblies, whereas 96% of the IH group specimens and 99% of the MT specimens would survive. The lack of overlap between the upper and lower limits of reliability values emphasizes the statistically significant differences between groups; the MT group presented the highest reliability, the EH the lowest, and IH was positioned intermediate to the other groups.

Failure Modes
All specimens failed after SSALT. When component failures were evaluated together, failures comprised a combination of abutment screw bending or fracture, abutment bending or fracture, and implant fracture. Observed failure modes are described in Table 2.

### RESULTS

#### SLF and Reliability
The SLF values (means ± standard deviations) were 468 ± 97 N for IH, 486 ± 51 N for EH, and 759 ± 52 N for MT.

The beta value means (confidence intervals) and associated upper and lower bounds derived from use-level probability Weibull calculation (probability of failure vs number of cycles) were 3.34 (2.22–5.00), 1.72 (1.14–2.58), and 1.05 (0.60–1.83) for groups EH, IH, and MT, respectively. These indicate that fatigue was an accelerating factor in all groups (Table 1).

The step-stress–derived probability Weibull plots and summary statistics at a 150-N load are presented in Fig 2 and Table 1, respectively. The SSALT permitted estimates of reliability at a given load level (Table 1). The calculated reliability with 90% confidence intervals for a mission of 50,000 cycles at 150 N showed that the cumulative damage from loads reaching 150 N would lead to implant-supported restoration survival of only 31% of EH assemblies, whereas 96% of the IH group specimens and 99% of the MT specimens would survive. The lack of overlap between the upper and lower limits of reliability values emphasizes the statistically significant differences between groups; the MT group presented the highest reliability, the EH the lowest, and IH was positioned intermediate to the other groups.

#### Failure Analysis
The failed samples were visually inspected and classified according to the proposed failure criteria (bending, fracture) for comparisons between groups. To identify fractographic markings and characterize the origin of failure and direction of propagation, the most representative failed samples of each group were inspected first under a polarized light microscope (MZ-APO stereomicroscope, Carl Zeiss MicroImaging) and then by scanning electron microscopy (SEM) (Model S-3500N, Hitachi).26

### Table 1 Calculated Reliability for a Protocol of 50,000 Cycles at a Load of 150 N

<table>
<thead>
<tr>
<th>Output</th>
<th>EH</th>
<th>IH</th>
<th>MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>0.4650</td>
<td>0.9912</td>
<td>1.0000</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.3187*</td>
<td>0.9687**</td>
<td>0.9994***</td>
</tr>
<tr>
<td>Lower</td>
<td>0.1812</td>
<td>0.8917</td>
<td>0.9922</td>
</tr>
<tr>
<td>Beta</td>
<td>3.34 (2.22–5.00)</td>
<td>1.72 (1.14–2.58)</td>
<td>1.05 (0.60–1.83)</td>
</tr>
</tbody>
</table>

Different numbers of asterisks denote statistically significant differences.
For the EH group, most failures involved abutment screw fractures, whereas the abutments and implants remained intact after mechanical testing. For the IH group, abutment screw and implant fractures were the chief failure modes. This group was the only one that showed longitudinal fractures in the implant neck area. Similarly to the EH group, the abutments were also intact. In the MT group, abutment and abutment screw bending or fracture were the main failure modes. All abutments and their screws fractured or bent, whereas the implants remained intact in this group (Fig 3, Table 2).

Observation of the polarized-light and SEM images of the fractured surfaces of the abutment screws allowed the consistent identification of fractographic markings (e.g., compression curl), fracture origins, and the direction of crack propagation (Fig 3).

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DISCUSSION

Because of the relevance of the mechanical characterization and failure patterns of different implant-abutment configurations in clinical practice, the present study used SSALT in single-unit anterior crowns cemented to implants with EH, IH, and MT connections to gain insight into the reliability of each interface. The use of accelerated life testing in dental research has been reported for several prosthetic restorative systems, where close similarity with the failures observed clinically could be simulated with this methodology in the laboratory.31–34 Its use in testing a variety of implant-abutment systems and scenarios has also been reported.35–38 The rationale is to reduce testing time by causing the samples to fail more quickly, yet with relevant failure mechanisms compared to SLF tests. The MT group presented the highest reliability, followed by IH and EH. These findings are in agreement with previous fatigue studies, which observed improved fatigue behavior for IH relative to EH connections.5,23 The stress magnitude was the highest in abutment screws of EH, followed by IH and MT connections10; therefore, the present findings of fracture in all EH and IH abutment screws but only half of the MT abutment screws are in agreement with Pessoa et al10 and suggest the relevance of the potential outcome (fracture) of such stresses when translated to laboratory fatigue testing.

The reported cumulative incidence of screw or abutment loosening in single-unit implant-supported crowns with internal (whether IH or MT) connections is 12.7% after 5 years of clinical service.39 Specific to the MT connection, a recent prospective evaluation of more than 2,500 implant-supported prostheses in function for up to 6 years reported a very different incidence of abutment loosening of 0.37% for single-unit crowns.10 It has been suggested that, in the MT connection, lateral loading is resisted mainly by the tapered design, which hinders abutment micromovement. In addition, a high pressure is normally maintained in the matching area because of the tapered design, allowing maintenance of implant position through frictional forces.18

Implant fracture was only observed in the IH group. Despite this clinically negative failure scenario, significantly higher loads for failure initiation were observed for this group compared to EH, which explains the significantly higher reliability for IH. One potential reason for such failure behavior occurring under a worst-case loading scenario, as simulated in the present study, is the minimum wall thickness demanded for this system, which resulted in enlargement of the implant’s coronal border during fatigue.41 On the other hand, in the MT connection, locking and friction have been reported as stabilization mechanisms, referred to as positive or geometric locking, and are assumed to be responsible for protecting the abutment threads from excessive functional load.18

The analysis of the failed implant components allowed the identification of fractographic markings and the tracing of the fracture origin and the direction of crack propagation. The ductile fractures, which occurred as a result of stresses surpassing the material’s yield or flow stress,42 showed a consistent crack pathway from lingual to buccal, where forces naturally occur and as was simulated in the present study.

The restoration of single-unit anterior spaces with implant-supported crowns is a challenging scenario in terms of longevity and esthetics. With regard to mechanical testing, the MT implant-abutment connection presented the highest reliability in maxillary central incisor replacements, followed by IH and EH connections. Although EH implants have been used successfully for splinted full-arch rehabilitations, it seems that they should be avoided in the anterior maxilla because of potential long-term complications.

CONCLUSIONS

The postulated hypothesis that implants with different abutment connections used as anterior single-unit replacements would show different reliability and failure modes when subjected to step-stress accelerated life testing was accepted. The Morse taper implant connection showed the highest reliability, followed by the internal hexagon and the external hexagon.

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REFERENCES