Probability of Failure of Internal Hexagon and Morse Taper Implants with Different Bone Levels: A Mechanical Test and Probabilistic Fatigue

María Prados-Privado, PhD1/Sérgio A. Gehrke, PhD, DDS2/Rosa Rojo, PhD, DDS3/Juan Carlos Prados-Frutos, PhD, MD, DDS3

Purpose: The goal of this study was to foresee the fatigue life of two implant connections, evaluate the failure probability with several bone levels, and compare the in vitro test results with finite element results.

Materials and Methods: Mechanical tests were done with 60 implants (Ø3.50 mm), and abutments were used. These implants were divided into two groups with 30 implants each: internal hexagon and Morse taper. Three bone levels and 10 implants for each level were analyzed. The first level was considered at the platform level, the second at 3 mm, and the last level at 5 mm above the platform resin. A quasi-static loading at 30 degrees was applied to the axis of the implant in a universal machine. Six models were created and assembled to reproduce the conditions used in the laboratory testing. All models had restricted all displacement at the bone (bottom and lateral). Loads employed in the numerical test were obtained experimentally. Loads and material properties were supposed to be random. Then, failure probability was calculated by the probabilistic methodology. Results: The internal hexagon group obtained the following mean fracture strengths: 2,092 N at the first level, 1,041 N at the second level, and 898 N at the third level. The mean fracture strengths for the Morse taper group were as follows: 1,687 N at the first level, 1,644 N at the second level, and 1,159 N at the third level. Results obtained by the finite element analysis are in accordance with the in vitro mechanical test results. The Morse taper group obtained a better behavior at bone levels 2 and 3 than the internal hexagon group. An important dependency between failure probability and bone level was found in the internal hexagon group. However, a similar behavior in levels 2 and 3 was obtained for the Morse taper group. Conclusion: In view of the mechanical results, the Morse taper group has a better behavior in bone levels 2 and 3 than the internal hexagon group. This is also in accordance with the probabilistic fatigue outcomes. Int J Oral Maxillofac Implants 2018;33:1266–1273. doi:10.11607/jomi.6426

Keywords: abutment, bone level, dental implant, failure probability, fracture strength, probabilistic approach

The use of dental implants has increased in the last few years in different clinical situations. This has more than a 90% success rate, but occasionally, prosthetic implants fail because of mechanical or biologic causes. Long-term evaluation of dental implants is essential for acquiring as much information as possible about the causes of implant success and failure. A high number of studies deal with the mechanisms to retrieve fractured implants and the causes of that failure. As detailed by Tiossi et al, biomechanical behavior of implant-supported prostheses has been analyzed with various techniques, such as photoelasticity, strain gauges, and finite element analysis.

An adequate crestal bone level is very important in the success of dental implants. Several factors such as excessive occlusal forces, the loss of peri-implant crestal bone, infections, implant-abutment gap, and surgical procedure, to name a few, can compromise the implant treatment.

The finite element method (FEM) is the most common technique used in dental and orthopedic...
Physiologic loads are very difficult to reproduce in experimental studies. Also, in vivo studies have limitations due to the ethical and technical restrictions. Although FEM has fewer limitations than in vivo and in vitro techniques, the accuracy of the predictions of these methods depends strongly on the quality of the mesh, the precision of the material data, boundary conditions, and assumed loading configuration.

A wide variety of implant designs are available nowadays in the market, and most of them comply with the quality requirements defined by ISO 14801. This standard details how the fatigue test of dental implants must be conducted to get the certification. According to ISO 14801, fatigue testing should be done by applying alternative loading (worst-case conditions) on the examined structures at several load levels until a lower load limit is reached (endurance limit). Below this limit, no fatigue failure is expected to occur.

Nowadays, it is possible to estimate the fatigue life of a component with different testing methods. The most common method is the “total fatigue life approach,” which is carried out to evaluate how many cycles can support a component until fracture. The results are synthetized in what is known as the Wöhler curve or S-N curve.

This study presents an alternative to the traditional fatigue life approach. This study employed a probabilistic fatigue in silico model on dental implants and their components, considering as random variables the material data and the loading configurations from an in vitro study. The main novelty of this study is that, unlike most of the previous finite element analyses, this study was done with a probabilistic point of view, based on the probabilistic FEM and a cumulative damage model, which is based on Markov chains.

The impact of the variability of multiple variables can be measured by probabilistic models. The goal of this study was to foresee the fatigue life of two implant connections, evaluate the failure probability with several bone levels, and compare the in vitro test results with finite element results.

### MATERIALS AND METHODS

Two dental implant models and their components (abutments and screws) were employed in this study. These implants are manufactured by Implacil De Borcoli, and their characteristics are described in Table 1 and shown in Figs 1 and 2.

<table>
<thead>
<tr>
<th>Group</th>
<th>Connection</th>
<th>Implant diameter × length (mm)</th>
<th>Abutment diameter × length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Internal hexagon</td>
<td>3.5 × 13</td>
<td>3.5 × 10</td>
</tr>
<tr>
<td>2</td>
<td>Conical Morse taper</td>
<td>3.5 × 13</td>
<td>3.5 × 10</td>
</tr>
</tbody>
</table>

**Fig 1** Internal hexagon implants tested. (a) Schematic drawing. (b) Transverse cut.

**Fig 2** Morse taper implants tested. (a) Schematic drawing. (b) Transverse cut.
Each group was studied with three different bone levels, as shown in Fig 3.

Mechanical Test with Static Compressive Forces
Sixty dental implants (Ø3.50 mm) and 60 abutments were manufactured by Implacil De Bortoli (Brazil). The geometric characteristics of these implants are detailed in Table 1. Two implant models were used in the final analysis: internal hexagon and conical Morse taper. International Organization for Standardization (ISO) guidelines were followed to test the static fatigue strength of the dental implants; these guidelines recommend the use of the smallest diameter of implant available for each model due to the adverse impact on the efficacy of the implant. The load was applied with an angle of 30 degrees with respect to the implant. Ten implants per level and group were fixed in epoxy resin. These levels were as follows: surface level (L1); 3 mm above surface level (L2); and 5 mm above surface level (L3), simulating various marginal bone levels (Fig 3). The epoxy resin had a Young’s modulus of elasticity like the cortical bone. All abutments received a torque of 25 Ncm, as recommended by the product manufacturer. A metal hemisphere was elaborated and cemented on the abutment. Then, a quasi-static load test until fracture was carried out to all implants in a properly calibrated universal testing machine (model AME-5kN, Técnica Industrial Oswaldo Filizola Ltda) with a test capacity of 5.0 kN. Tests were carried out at the Testing Laboratory of Biomechanics (Biotecnos). The test speed was set at 1 mm/min.

Once the quasi-static loading test was finished, all fractured implants were ultrasonically cleaned in 96% isopropanol and observed under low-power magnification. Digital photographs were taken using a high-resolution camera (Sony Cyber-shot DSC-H9, Sony), and the data were reported descriptively. Then, the samples were completely embedded in a metallographic resin to cut. All samples were cut in the center portion of the longitudinal axis of the sets (implants plus abutments) using a metallographic cutter (Isomet 1000), and a diamond disk was used to produce cuts at the center of the longitudinal joint. The joints were then polished using a sequence of papers that were 240-, 320-, 400-, 600-, and 1,200-grit abrasive (Poli-pox), plus a rag wheel to provide appropriate surface smoothness.

Finite Element Model
Six three-dimensional models were created using the computer-aided design (CAD) software SolidWorks 2016 (Dassault Systèmes, SolidWorks). Three different marginal bone levels were represented in each group with the aim of reproducing the experimental results obtained in a study by Gehrke et al.2 All geometries of the model were provided by the manufacturer except the cylinder, which was created employing SolidWorks.

All assembled models were imported into ANSYS Workbench 16 and analyzed. A change of less than 5% in von Mises stress in the model was considered as a criterion of convergence.15 Due to the stress singularities in sharp corners, it is crucial to have a good mesh in the model. The number of elements and nodes employed in this study are summarized in Table 2.

Material Properties
The elastic properties of the materials used in the models were taken from the literature, as shown in Table 3. Implants and bone were modeled with linear, elastic, isotropic, and homogenous properties.16 Cylindrical geometry was modeled with cortical bone properties due to its similarities to this material.5 To develop this model, the stochastic values (mean and standard deviation) of the material properties and loads should be known. In this case, stochastic values of materials and loads are shown in Tables 3 and 4, respectively. The ultimate stress is an important value to know the limits of behavior of a material. The ultimate stress of cortical bone has been described as 170 MPa in compression and 100 MPa in tension.17

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**Fig 3** Bone levels examined in this study.
Boundary Conditions and Loading Configuration

Osseointegrated screw implants with various marginal bone levels were simulated in the present study: surface level (L1), 3 mm above surface level (L2), and 5 mm above surface level (L3).

A torque of 25 Ncm was applied in the abutment, as recommended by the product manufacturer.

All models employed in the present study were constrained as detailed in Fig 4: all degrees-of-freedom in the bottom and lateral surfaces of the bone were restrained. To simulate an osseointegrated condition, the implants were rigidly bonded in the bone.

Probabilistic Fatigue Model

In addition to the previous deterministic finite element analysis, a probabilistic fatigue model was also performed. Load and Young’s modulus were considered as random variables, and they were handled via first-order Taylor series expansion. Once all the sensitivities of the random variables are known, it is possible to apply the mean and variance operator. All the sensitivities of the random fields involved, such as displacement field, strain field, and stress field, can be obtained as described in Prados-Privado et al.

The aim of this model is to compute the random output variable and fatigue life, and obtain the mean life and variance. Now, the use of a damage model, based on Markov chains, is necessary.

Finally, the probabilistic transition matrix (PTM) can be obtained from the mean value and variance of the fatigue life, and from this PTM, it is possible to calculate the failure probability.

RESULTS

Mechanical Tests

Different static loads, depending on the bone level, were obtained with 30 degrees to the implant axis as shown in Table 4. Images were captured using a digital microscope to evaluate the fractures (Figs 6 and 7).

Experimental fracture loads obtained in the mechanical test were used to check that the failure area
corresponded with the results calculated by the finite element model, and then, the probabilistic fatigue model was computed to compare the effect of different levels of marginal bone in the long-term fatigue in dental implants.

Internal hexagon implants obtained the highest loads at level 1, with a mean load of 2,092 N. However, Morse taper obtained more resistance at levels 2 and 3 than internal hexagon.

A fracture of the abutment appeared in all bone levels for internal hexagon implants. However, a similar behavior in levels 2 and 3 was obtained for the Morse taper group. A deformation in the cervical portion of the implant, with a mean load of 1,687 N, appeared at the first level. In the second level, there was also a deformation of the implant, with a mean reduction of 2.5% of loads and a fracture of the abutment. At level 3, a deformation of the implants appeared, and the load was reduced 29.5% in relation to level 2.

### Table 4  Mean ± SD of Resistance Values Obtained in Mechanical Quasi-static Test

<table>
<thead>
<tr>
<th>Implant group</th>
<th>Force (N) Level 1</th>
<th>Force (N) Level 2</th>
<th>Force (N) Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal hexagon group</td>
<td>2,092 ± 200</td>
<td>1,041 ± 100</td>
<td>898 ± 50</td>
</tr>
<tr>
<td>Morse taper group</td>
<td>1,687 ± 200</td>
<td>1,644 ± 180</td>
<td>1,159 ± 300</td>
</tr>
</tbody>
</table>

**Finite Element Method and In Vitro Study**

In this study, von Mises stress on implants, screws, and abutments was used to assess the effect of the marginal bone in the fatigue behavior. Results obtained in an in vitro study matched with the results obtained with the three-dimensional finite element model detailed in the present study. Figures 8 and 9 show a macro picture of dental implant failure after the mechanical tests. Internal hexagon at level 1 showed the highest stress value in the hexagon. At level 2, the maximum stress appeared near the area of the implant insertion into the bone, and, at level 3, the maximum value appeared, again, in the hexagon. The conical Morse taper implants at level 1 showed a higher stress level in the cervical part of the implant. At level 2, the maximum stress value also appeared in the first thread of the implant and, finally, at level 3, the highest stress values obtained with this finite element model were concentrated in the body of the implant, where the bone appears.
Probabilistic Fatigue

Failure probability of two different implant designs with three different marginal bone levels was obtained employing the probabilistic methodology. To calculate the probability of failure, it is necessary first to obtain the PTM, which is a matrix that represents the probability of moving from one damage cycle to the next in a one-time step.

Table 5 shows the data to construct the PTM in each case: where dimension represents the size of the matrix. In this case, all matrixes are rectangular, which means that the number of rows and columns is the same. This matrix depends on the $p$ (probability of remaining in the same damage cycle) and $q$ (probability of jumping to the next damage cycle). More details are included in the Prados-Privado et al study.14

The probability of failure in the internal hexagon group was obtained from 1 million loading cycles to 10 million cycles. As explained by Gibbs et al,19 1 year of in vivo service corresponds with, approximately, 1 million cycles. In Fig 10, the probability of failure in the internal hexagon group shows an important dependency of the bone level, while in the Morse taper group, the implant and its superstructures have a similar behavior when the bone loss is small (Fig 11). With this methodology, the probability of failure in a system can be determined for a specific number of loading cycles (Figs 10 and 11). In level 1, the internal hexagon group has a better fatigue behavior in terms of probability of failure than the Morse taper group because the probability of failure in this level remains equal to zero until 5 million cycles, while for a Morse taper, this probability is equal to zero until 3 million cycles. At levels 2 and 3, the probability of failure remains equal to zero for fewer cycles in internal connections than in Morse taper implants, which means that internal connections have a higher risk of failure than Morse taper connections. The probability of failure remains equal to zero until 3 million cycles in Morse taper implants at levels 1 and 2; however, once the failure probability is different than zero, level 2 has fewer cycles for the same probability than level 1.

**DISCUSSION**

This in vitro study examined the maximum fracture of load of two dental implant connections with three different bone levels. The methodology proposed in the present study was applied with two dental implants with different internal connections (hexagon and Morse taper) and three marginal bone levels (L1 = 0 mm, L2 = 3 mm, and L3 = 5 mm). The results obtained in this mechanical test were used to compute the finite element analysis and the probabilistic study.

Fracture loads obtained in the in vitro mechanical test, similar to a previous study published by Gehrke et al,2 which were employed to compare the results obtained by the three-dimensional finite element model employed here, are in accordance with the results obtained by the mechanical test. Therefore, the worst scenario in terms of loads was simulated with the goal of obtaining the probability of failure of the implants analyzed in the present study. In view of the mechanical results, the Morse taper group had a
better behavior in bone levels L2 and L3 than the internal hexagon group. This is also in accordance with the probabilistic fatigue outcomes.

Several assumptions have been made in the present study. Bone has been modeled as isotropic, although it is anisotropic. All implants were assumed to be 100% osseointegrated. In the present study, bone has been modeled as a cylinder and considered as a compact bone.

Thus, this finite element analysis has limitations. Only forces in one direction have been applied; however, combined loads should appear for a more realistic analysis, but here, due to a comparison between the in vitro analysis and FEM, it is not necessary to consider load components in more directions. Another limitation is that this study does not include other factors, different from biomechanical ones, that can interfere in bone loss.

To the best of the authors’ knowledge, there are no studies in the literature analyzing internal hexagonal connection and Morse taper implant behavior from a probabilistic point of view or their behavior under different bone loss levels.

Since the fatigue resistance of implants is very important for long-term clinical success, the present study employed a probabilistic methodology to analyze the probability of failure in dental implants, abutments, and screws, keeping in mind the influence of different random variables, such as material properties and loads. The model proposed in this study allows for obtaining the influence of the uncertainty of mechanical factors on implant behavior with different marginal bone levels. Mastication habits cannot be considered as deterministic because different patients cause different loads on implants. Thus, the study of dental implants requires a probabilistic approach as the model employs here. However, most of the finite element studies on dental implants available in the literature are deterministic.

Marginal bone level is a key criterion of long-term success in dental implant treatment, and this bone level position is influenced by numerous variables related to surgical trauma, prosthetic considerations, implant design, bone substratum, patient habits, implant-abutment connection, and the general health of the patients.

Von Mises stress is widely used in dental implant analysis because, as Erkm et al explained in their study, these values are defined as the beginning of deformation for ductile materials.

FEM has been widely used in dental implant studies because it is considered to be an excellent tool to analyze realistic biomechanical problems and because it is a powerful tool to simulate dental restorations.

Further studies simulating different random variables and considering the anisotropic and regenerative properties of bone are needed.

From the clinical point of view, it is generally observed that implants with internal hexagonal and Morse taper connections present a better behavior in front of the hexagonal external connections in terms of marginal bone loss. This study suggests that the clinical results would be more favorable for the Morse taper connection. Likewise, the behavior of the best connections available in the clinical field for different bone insertions was evaluated, but only from the biomechanical point of view.

CONCLUSIONS

Although some assumptions have been employed in the three-dimensional finite element model and even though it is very difficult to exactly reproduce the natural behavior, this mathematical model has more repeatability and controllability than in vitro studies. Results obtained by finite element analysis can provide more in-depth information than mechanical tests, and the probabilistic model employed here can be used to predict the long-term behavior of dental implants, which is helpful in reducing redundant clinical experiments. In view of the mechanical results, the Morse taper group has a better behavior in bone levels L2 and L3 than the internal hexagon group. This is also in accordance with the probabilistic fatigue outcomes.

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