Mechanics of the Implant-Abutment Connection: An 8-Degree Taper Compared to a Butt Joint Connection

Beat R. Merz, Dr sc techn, MBA[1]/Stephan Hunenbart, Dipl Eng TU[2]/
Urs C. Belser, DMD, Prof Dr med dent[3]

This paper presents a comparison between the 8-degree Morse Taper and the butt joint as connections between an implant and an abutment. Three-dimensional, non-linear finite element models were created to compare the 2 connection principles under equal conditions. The loading configuration was thereby modeled according to a test setup actually used for the dynamic long-term testing of dental implants as required for regulatory purposes. The results give insight into the mechanics involved in each type of connection and are compared to actual findings with the testing machine. The comparison indicates the superior mechanics of conical abutment connections and helps to explain their significantly better long-term stability in the clinical application. (INT J ORAL MAXILLOFAC IMPLANTS 2000;15:519–526)

Key words: *dental implants, finite element analysis, mechanical stress*

While the high rate of success of dental implants with respect to osseointegration has become an accepted clinical reality, numerous reports about the high incidence of technical complications, such as abutment and occlusal screw loosening, have been published. Although these problems usually do not lead to the loss of an implant, they present a problem for both clinicians and patients and result in additional cost.

Implants featuring a short (< 2 mm) external hex at the prospective connection with the abutment seem to be especially prone to screw loosening, since all external force components, except for the axial compressive force, are concentrated mainly on the abutment screw. Typically, a high incidence of screw loosening of up to 40% was found for this type of abutment connection, as reported by Jemt et al[1] and by Becker and Becker.[2] In contrast, Levine et al[3,4] reported a far lower rate of abutment loosening (3.6% to 5.3%) with conical implant-abutment connections, restoring single-tooth replacements with cemented crowns. In general, screw loosening seems to occur most often with single-tooth implant restorations, with the molars being the most difficult to keep tight.[5]

Sutter et al[6] proposed an 8-degree taper connection, referred to in the literature as the ITI Morse Taper, between implant and abutment as an optimal combination of predictable vertical positioning and self-locking characteristics. Similar results were reported by Norton,[7,8] who showed that the incorporation of conical connections between implant and abutment dramatically enhanced the ability of the system to resist bending forces. To date, experiences published by Levine et al[3,4] and Felton[9] confirm this view.

It was therefore the objective of the present study to enhance the understanding of the mechanics of these 2 types of abutment connections. For this purpose, 3-dimensional non-linear finite element (FE) models were created to compare taper joints and butt joints and to interpret results in light of findings of cyclic loading tests performed on the actual implant-abutment complex.

[1]Senior Manager, Development & Engineering, Institut Straumann AG, Waldenburg, Switzerland.
[2]Engineer, Development & Engineering, Institut Straumann AG, Waldenburg, Switzerland.
[3]Professor and Chairman, Department of Prosthodontics, School of Dental Medicine, University of Geneva, Geneva, Switzerland.

Reprint requests: Dr Beat R. Merz, NMT Management AG, Elisabethenstrasse 23, CH-4051 Basel, Switzerland. Fax: +41 61 270 3500. E-mail: fgfgg@datacomm.ch

COPYRIGHT © 2000 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY. NO PART OF THIS ARTICLE MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

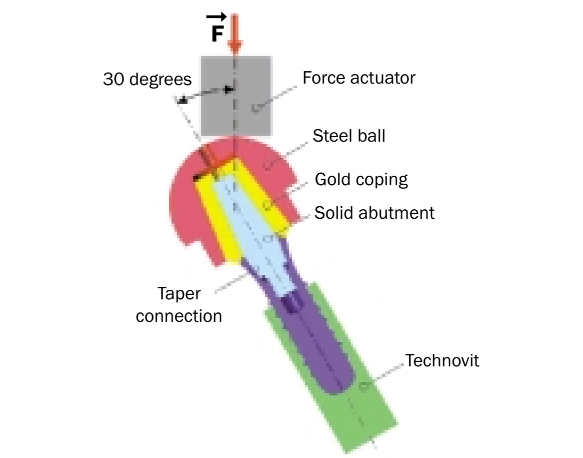


Fig 1 Setup of the test configuration employed for cyclic testing. The ITI 12-mm solid-screw implant is combined with the 7-mm high, 6-degree solid abutment and a steel ball, which represents the crown, for loading by the force rod. The embedding material is positioned 2 mm lower than the normal bone level, representing bone resorption, to further aggravate the testing conditions.

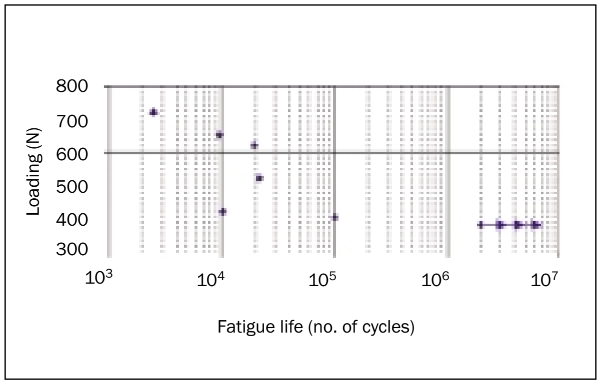


Fig 2 Stress-cycle diagram of a series of measurements taken in the test setup according to Fig 1. All implants were of the same material and production lot. The loads were decreased until 3 implants survived for 2 million cycles (indicated by 3 arrows). In the given series, this long-term cyclic strength was found at 380 N, but this value is subject to slight variations with different production and material lots.

Table 1 Material Parameters Utilized for the Finite Element Calculation

Material	Young's modulus (N/mm^2)	Poisson no.
Commercially pure titanium grade 4	114,000	0.369
Steel	210,000	0.3
Gold alloy	170,000	0.3
PMMA	3,000	0.3

MATERIALS AND METHODS

An FE model was created that combined a 12-mm ITI solid-screw implant with a 6-degree abutment 7 mm in height (ITI Dental Implant System, Institut Straumann, Waldenburg, Switzerland). The model reflected the testing configuration currently employed for testing implants, eg, for clearance by the Food and Drug Administration (Fig 1). The implant was embedded into a polymethyl methacrylate resin (PMMA) cylinder (Technovit 4071, Heraeus Kulzer, Wehrheim, Germany), which in turn can be fixed in the testing machine. Crestal bone resorption of 2 mm, compared to the normal bone level, was simulated by setting the PMMA level 2 mm apically to the border between the machined portion of the implant and the titanium plasma-sprayed (TPS) or sandblasted surface (sandblasted, large grit, acid-etched [SLA]), to test the configuration under critical conditions. A gold coping was fixed to the solid abutment; it carries a steel "crown" in ball form, which is used for imposing the dynamic loading by the testing machine. During cyclic loading, the implant was completely immersed in a saline solution (0.9% sodium chloride at 37°C). To obtain a stress-cycle diagram of a given configuration, a series of implants was submitted to the test, starting at very high loads and reducing these loads until 3 implants survived 2 million cycles. Figure 2 shows the results of a series of measurements of ITI implants in the stress-cycle diagram. All implants in that measurement series were of an identical material and production lot.

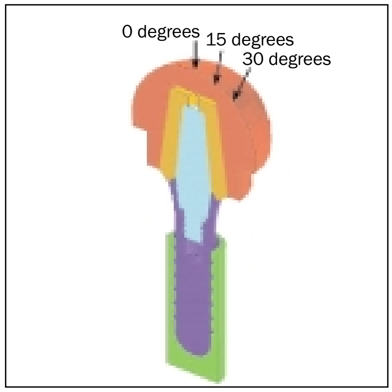
Models

Because the implant-abutment complex is symmetric, only half on the configuration needed to be modeled (Figs 3a and 3b). To simplify the model, the threads were not represented in their spiral characteristic but took the form of symmetric rings. Non-linear contact with friction was assumed between the abutment and the implant in the taper joint, as well as in the thread portion, and between the gold coping and the 45-degree shoulder at the implant neck (Fig 1). This means that the contact zones transfer only pressure and tangential frictional forces, whereas tension is not transferred. All other contacts were assumed to be linear, ie, transferring compression as well as tension or shear. The material properties used are listed in Table 1. For the friction coefficients, Abkowitz et al[10] reported a value of 0.5 for dry titanium/titanium friction, Steinemann et al[11] found values of 0.43 to 0.53 for titanium in sodium chloride solution, and Sakaguchi

COPYRIGHT © 2000 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY. NO PART OF THIS ARTICLE MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

Fig 3a *(Left)* Finite element model of a 12-mm ITI solid screw with solid abutment. Arrows indicate the loading in different off-axis angles in the plane of symmetry.

Fig 3b *(Right)* Detail of the model in the area of the taper joint. The layer of yellow elements is used to introduce axial preload that results from tightening the abutment, by submitting the corresponding elements to a negative temperature difference, thus forcing a contraction.



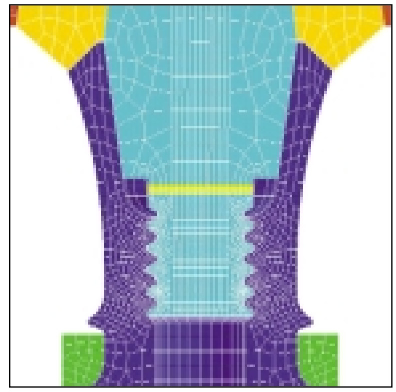
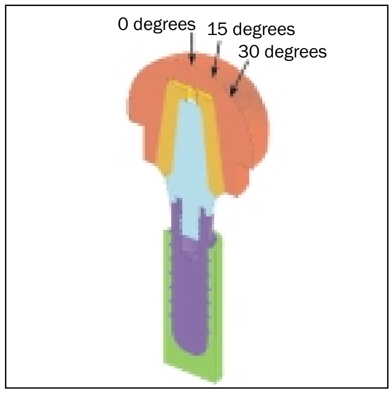
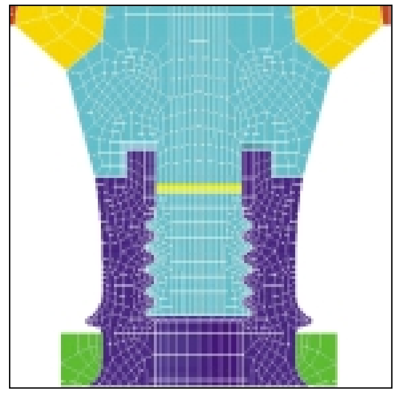


Fig 4a *(Left)* Finite element model of a 12-mm ITI solid screw with a hypothetical butt joint connection to the abutment.

Fig 4b *(Right)* Detail of the butt joint with the temperature elements (yellow) added for contraction.





and Borgersen[12] used a value of 0.4 for all contacting surfaces. In the present calculation, a value of 0.5 was assumed for friction between all surfaces.

To demonstrate the effects associated with the use of an 8-degree taper connection (Fig 1), a second model was created simulating the same implant-abutment complex with a hypothetical butt joint, similar to that of an external hex-type implant. Emphasis was given to creating a comparable situation with respect to lever arms, forces, and restraints. For instance, the first abutment threads were positioned at the same height for both models (Figs 4a and 4b).

Loading and Boundary Conditions

Loading and boundary conditions were identical for both models. The first load step simulated the tightening of the abutment with a torque of 35 N·cm as prescribed for the fixation of solid abutments or octa abutments.[3,6] When the ratchet is used to tighten the abutment, the tightening torque required to overcome the force moment (M) generated by thread friction and by friction in the joint is calculated by the following equation:

$$M_{\text{tightening}} = M_{\text{thread friction}} + M_{\text{joint friction}}$$

Through frictional forces, the torque is related to the resulting axial preload in the abutment, similar to the preload in a screw that applies between the thread and the screw head. Burguete et al[13] have published a detailed overview of the basic mechanics of screw tightening. In the present study, a simplified engineering formula[14] was utilized to determine the axial preload (F_v) from tightening moment (Fig 5):

$$M_{\text{tightening}} = M_{\text{thread friction}} + M_{\text{joint friction}}$$
$$= F_v \times (0.159 \times P + \mu \times 0.577 \times D_2)$$
$$+ F_v \times D_c \times \mu \times 1/\cos\alpha$$

where P = screw pitch, D_2 = mid-diameter of the flank of screw thread, D_c = mid-diameter of the cone, α = angle between implant axis and surface orthogonal in the cone (82 degrees), and μ = coefficient of friction. The preloads determined in this fashion amounted to 53.2 N for the taper joint and 358.6 N for the butt joint. The calculation also indicated that with the taper joint, 91% of the tightening torque is required to overcome friction in the conical connection, leaving only a limited strain that must be absorbed by the thread.

Copyright © 2000 by Quintessence Publishing Co, Inc. Printing of this document is restricted to personal use only. No part of this article may be reproduced or transmitted in any form without written permission from the publisher.

Second-order effects resulting from the spiral characteristic of the threads and from remaining torsion in the abutment were ignored in the present study. To control calculation of the preload and underlying assumptions, a special test setup was utilized. In this setup, ITI implants were cut into 2 pieces between the cone and the threaded portion of the implant and a measuring device was incorporated into the setup so as to effectively measure the axial preload resulting from tightening an abutment (Fig 6).

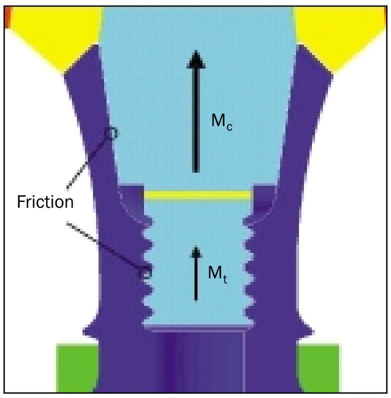


Fig 5 A tightening torque of 35 N·cm is required to overcome the moments of force resulting from friction in the thread (M_t) and in the cone or butt joint portion (M_c) of the abutment. Between the gold coping and the 45-degree shoulder of the implant, there is no friction at tightening. Clinically, the coping would not be present when connecting the abutment, and in the model a small initial gap prevents friction.

The determined axial preload was introduced into the model with the help of a layer of temperature-sensitive elements between the implant body and the cone or butt joint (Figs 3b and 4b). These were submitted to a negative temperature difference, which resulted in a contraction such that the required tension was generated. Since a coping is usually not yet in place when tightening an abutment, a corresponding tolerance was introduced between the coping and the implant shoulder in the taper model. This tolerance was designed such that it was just closed in this first load step, but created no contact forces on the 45-degree shoulder of the implant (Fig 1).

For the following load steps, additional loads of 380 N were introduced, acting on the steel ball exactly in the plane of symmetry in angles of 0 degrees, 15 degrees, and 30 degrees off-axis, with 30 degrees being the loading angle employed in the actual cyclic testing (Fig 1).

For the boundary conditions, all nodes on the outside of the PMMA cylinder were locked to simulate the fixation in the testing machine. Furthermore, the nodes in the symmetry plane were restrained to remain within the plane, to account for symmetry.

RESULTS

The first step of loading, ie, tightening the abutment, leads to a symmetric stress distribution in the connection area of the implant and abutment in both

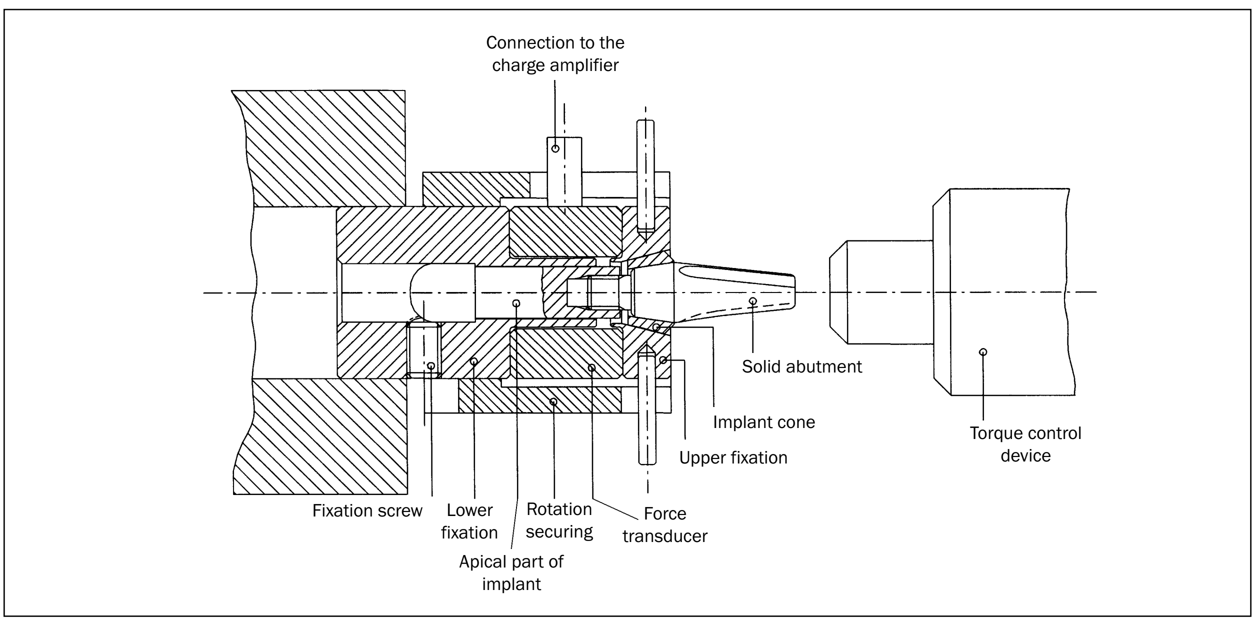


Fig 6 Test setup for measuring the actual axial preload in abutments tightened with a given torque. The conical implant neck is separated from the implant body, and the axial force in between is measured with a force transducer. To ensure fixation of the implant, the outside threads were removed.

COPYRIGHT © 2000 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY. NO PART OF THIS ARTICLE MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

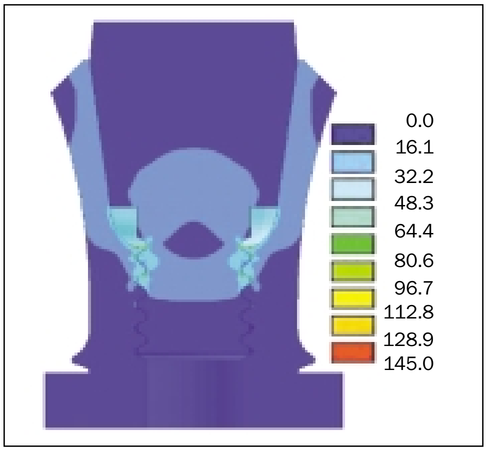


Fig 7a Distribution of equivalent stress (MPa) in the ITI Morse Taper after tightening to a torque of 35 N·cm. The situation is symmetric, so stress levels remain low. The gold crown and steel ball are not shown, since clinically they would not be present when tightening the abutment. In the model, this is accounted for by introducing a small gap between the gold coping and the implant shoulder, which is closed when the axial preload is imposed.

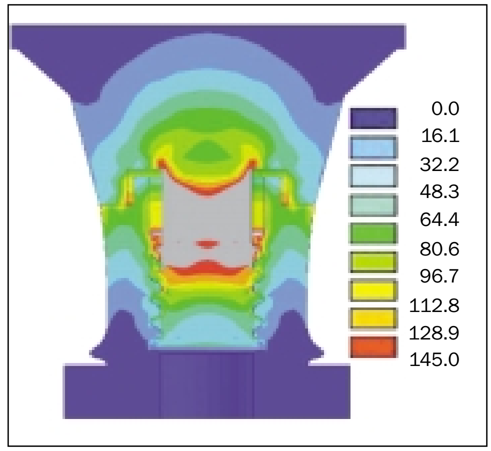


Fig 7b Distribution of equivalent stress (MPa) in the butt joint model after tightening to 35 N·cm. Higher stresses are experienced, as compared to the taper connection (Fig 7a) because of the higher required axial preload resulting from this joint configuration. However, the stress levels reached are still clinically acceptable.

models. The tapered connection experiences a wedge effect, while in the abutment it is primarily the first 2 threads that are under stress. As is typical in a screw connection, the strain in the first 2 threads is concentrated on the surface, while the interior experiences lower stress levels (Fig 7a). Figure 7b depicts the butt joint under the same torque with color coding identical to Fig 7a. Significantly higher stress levels were found throughout the butt joint connection. However, the induced stress still appears to be unproblematic from a mechanical point of view.

The preloading tests with 10 ITI implants with the abutment configuration cut into 2 pieces (Fig 6) revealed an effective average preload of 46.8 N (± 9.7 N) and compared favorably with the value calculated in the FE models.

Figures 8 to 10 show the distribution of equivalent stress resulting from the different outside loads following abutment tightening in loading, both axial and off-axis. Under a purely axial load of 380 N, the abutment is pressed into the taper connection. In addition to the taper, the 45-degree shoulder now absorbs part of the load transfer. The pre-stress in the threads, on the other hand, is released. The situation remains symmetric and stress levels are low on all parts (Fig 8a). The same applies to the butt joint where a certain pre-stress remains in the thread area (Fig 8b).

With a 15-degree off-axis orientation of the load, the situation becomes asymmetric. On the side facing the external load (right in Figs 9 and 10), the implant and the abutment experience tension stress from bending, while on the opposite side the connection is subject to compression. The majority of the load transfer from the abutment to the implant takes place through the taper connection. In addition, some load is taken up by the 45-degree shoulder on the pressure side. The screw threads, however, are only subject to a very limited stress in the tapered connection (Fig 9a). The butt joint design, on the other hand, leads to far higher tensile stresses in the screw threads on the side facing the load (Fig 9b). A typical bending stress distribution results in the screw portion of the abutment.

A 30-degree off-axis force application represents the most demanding load case in this series of calculations. Figure 10a provides an overview of the complete model; Fig 10b shows the situation in the joint area for the taper configuration. The stress levels have increased, but essentially basically the same load-transfer mechanisms are observed as described in Fig 9a. Still, the thread portion of the abutment is protected to a great extent by the taper connection. Maximal tension stress experienced at the thread root on the tension side is calculated as 1,176 MPa. This value is high when considering the strength of titanium against cyclic loading. However, the area where it applies is extremely limited, such that supporting effects related to the small size of the stress area (ie, the steep stress gradient[15]) exert a positive influence and grant the survival of the restoration against cyclic loading of 350 N to 380 N, as was demonstrated in the actual laboratory

COPYRIGHT © 2000 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY. NO PART OF THIS ARTICLE MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

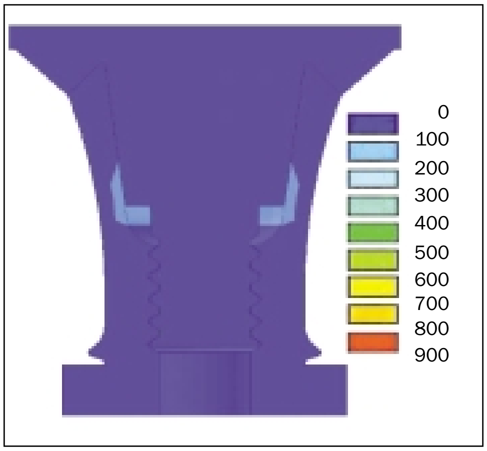


Fig 8a Distribution of equivalent stress (MPa) in the ITI Morse Taper design under straight axial loading of 380 N. The preload in the thread is compensated (relieved) while the conical abutment portion is further wedged into the implant and therefore maintains the intimate connection.

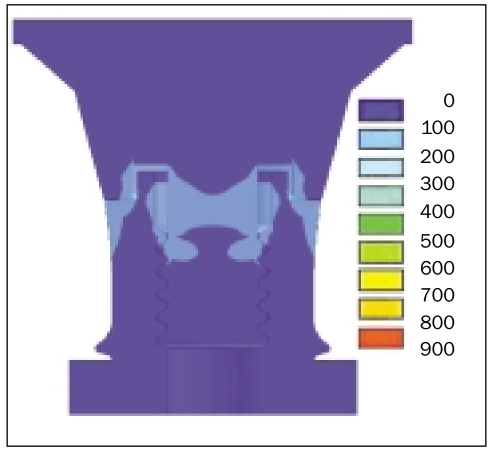


Fig 8b Distribution of equivalent stress (MPa) in the butt joint under straight axial loading of 380 N. The preload of the thread is largely compensated. Since the thread actually belongs to a screw separate from the abutment, its stability against loosening is reduced at that moment.

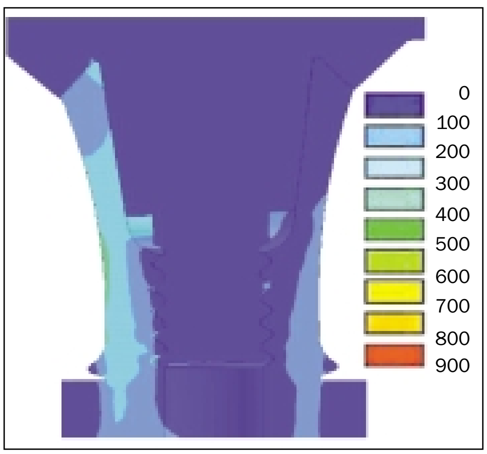


Fig 9a Distribution of equivalent stress (MPa) in the ITI Morse Taper under 15-degree off-axis loading of 380 N. The left side of the implant is under pressure, and the right side is under tension. The thread portion experiences very low stress values.

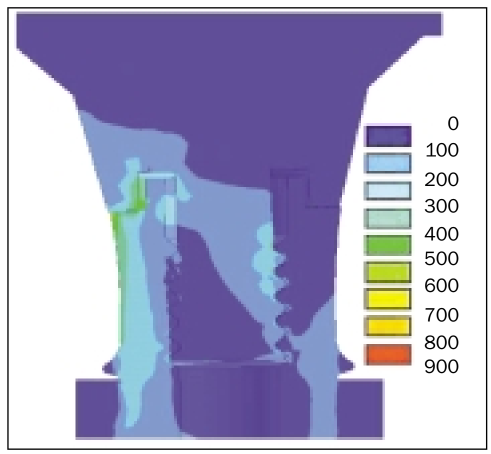


Fig 9b Distribution of equivalent stress (MPa) in the butt joint under 15-degree off-axis loading of 380 N. The left side of the implant is under pressure, and the right side is under tension. Although the values are not yet critical, the tension side of the thread experiences stresses 2 levels higher than in the taper design (Fig 9a).

test series. In the case of the butt joint, the difference from the still-viable stress distribution of the taper joint is dramatic. The maximal tension reached in the thread is 1,403 MPa. In contrast to the taper joint, the areas of stress beyond the cyclic strength are no longer small, such that no supporting effects can be claimed. Figure 10c also indicates the loss of contact in the butt joint on the right side, while the left side experiences very high compression, exceeding the threshold of plasticity.

DISCUSSION

Together with proper design of the occlusion and stable osseointegration, a reliable connection between implant and abutment is an important precondition for the appropriate functioning and stability of implant restorations,[7] especially cemented ones.[9] Several clinical studies[1–4,9] report widely varying incidences of abutment loosening for different types of abutment connections. In particular, external hex configurations seem to be prone to

COPYRIGHT © 2000 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY. NO PART OF THIS ARTICLE MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

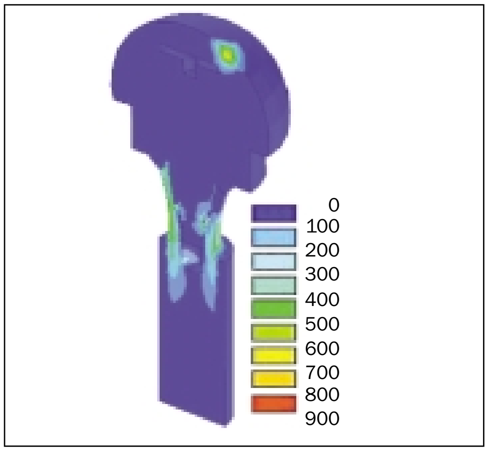


Fig 10a Overview of the ITI Morse Taper model under 30-degree off-axis loading of 380 N. The right side is under tension, and the left side is under compression. On the steel ball, the location of force application is apparent with high stress values.

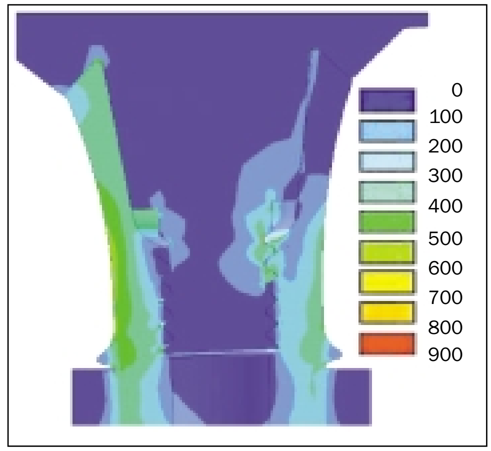


Fig 10b Distribution of equivalent stress (MPa) in the ITI Morse Taper under 30-degree off-axis loading of 380 N. The thread is still largely protected by the conical joint. The areas with critical stress levels in the abutment thread are extremely limited and small. Therefore, supporting effects come into action.

abutment screw loosening, while the conical connection of the ITI Morse Taper compares clinically very favorably.[3,4,9]

Basically, the external hex configuration and the taper connection employ quite different mechanical principles of function. In the external hex configuration, the axial preload of the abutment screw is a determining factor for stability of the connection.[12,13] This screw alone secures the abutment, eg, under horizontal loading. There is no form lock or positive locking by the external hex, which determines the rotational position but does not absorb any lateral loading (Fig 10c). Therefore pure clamping is the underlying principle.[16] The optimal preload corresponds theoretically to the yield point of the screw. The aim of tightening is to achieve the optimum preload that will maximize the fatigue life, while offering a reasonable degree of protection against loosening.[13] In practice, the achievable preload is limited by the super-position of additional tension related to the external loading. For instance, Haack et al[16] reported a preload of 60% of yield strength for gold alloy screws when torqued to the recommended 32 N·cm.

In a taper connection, form lock and friction are the basic principles. Lateral loading is resisted mainly by the taper interface, which prevents the abutment from tilting off, even when the connection between the taper section and the thread of the abutment is lost, eg, because of a fracture. The same mechanism, referred to as positive or geometric locking, is responsible for protecting the abutment threads from excessive functional load. There is no possibility of tilting about a single point or small area, as with an external hex. The longitudinal preload is limited to about 45 to 55 N, but because of the tapered design, a high normal pressure is maintained in the contact area, granting stable retention of position by frictional forces. With the low axial preload, the danger of reaching the yield load by superimposing external loads is very limited.

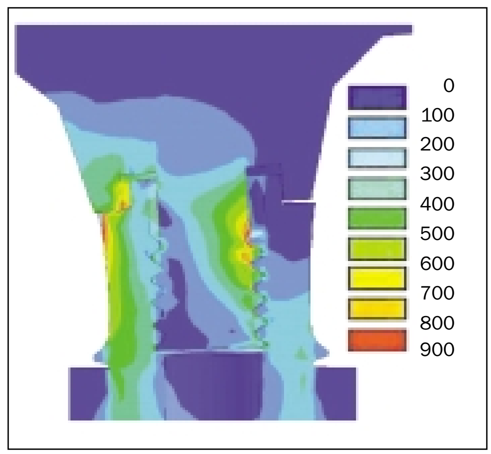


Fig 10c Distribution of equivalent stress (MPa) in the butt joint under 30-degree off-axis loading of 380 N. The stress levels on the tension side are high and spread over a large area. Therefore, supporting effects are nearly irrelevant. On the compression side, very high punctual loads are found in the butt joint area, while the abutment is separated from the implant shoulder on the tension side.

The present FE study supports the findings of long-term cyclic loading tests of the ITI Morse Taper. While mechanical testing merely shows if and where a system will break, the FE method provides insight into the inherent mechanics of a given technical system. It can depict the internal stress situation

COPYRIGHT © 2000 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY. NO PART OF THIS ARTICLE MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.

and show where the weak points of a system are located. Since contact and friction play important roles in the present application, a non-linear model must be used to obtain meaningful results. The FE model employed studied the stress and contact situation with a relatively high resolution in a 3-dimensional model, as compared to many much more simplified models found in the literature, which are usually restricted to a 2-dimensional or axisymmetric representation.[12,17] As a simplification, the present model, like the axisymmetric models, does not take into account the helical characteristic of the threads. However, there will be no effect of this modification as long as the implant is not submitted to moments about its longitudinal axis, ie, "screwing" it into or out of the enclosing material. Such moments are neither present in this model nor in the models cited.

The results of the calculations with loads applied at different angles show the importance of the taper connection in reducing the load on the screw portion of the abutment to a viable level. Furthermore, the taper prevents loosening under straight axial loading. While the tension preload of the thread might be completely compensated, the friction in the taper ensures a stable and rotation-free connection between implant and abutment. In a butt joint, on the other hand, this partial or complete compensation of the preload is likely to lead to loosening[13] over time. With loads of up to 15% in a slight off-axis direction, the threads are barely affected by the external load in the case of the taper joint. With loads applied at 30 degrees off-axis, the threads do experience some stress, which reaches higher than the yield point, but the area of high stress is very limited and the stress gradient is high, such that supporting effects apply.[15] This was proven in cyclic testing over 2 million cycles. As utilized in the present calculations, 380 N clearly represents a borderline load for the given implant-abutment combination with the ITI Morse Taper. The characteristics in the stress-cycle diagram have a certain bandwidth, depending on the material or production lot. For instance, in the series depicted in Fig 2, the fatigue strength, ie, the load that 3 implants survived for 2 million cycles, amounted to 380 N. Other test series led to an 8% lower fatigue strength of 350 N but never fell below that value. Under similar conditions, the butt joint compares less favorably. Even at limited off-axis angles of force application, the resulting stress at the abutment screw reaches far higher levels than in the taper case. With a load of 350 N to 380 N at 30 degrees off-axis, the areas of high stress beyond the yield point are too large to be compensated by supporting effects. Therefore, the FE calculation predicts failure of this configuration under the given load situation before 2 million cycles are reached.

ACKNOWLEDGMENTS

We thank Mr Hans Stoop and Dr Daniel Snétivy for providing Figs 2 and 6 and the related measurement values.

REFERENCES

1. Jemt T, Laney WR, Harris D, Henry PJ, Krogh PHJ Jr, Polizzi G, et al. Osseointegrated implants for single tooth replacement: A 1-year report from a multicenter prospective study. Int J Oral Maxillofac Implants 1991;6:29–36.
2. Becker W, Becker BE. Replacement of maxillary and mandibular molars with single endosseous implant restorations: A retrospective study. J Prosthet Dent 1995;74:51–55.
3. Levine RA, Clem DS, Wilson TG Jr, Higginbottom F, Saunders SL. A multicenter retrospective analysis of the ITI implant system used for single-tooth replacements: Results of loading for 2 or more years. Int J Oral Maxillofac Implants 1999;14:516–520.
4. Levine RA, Clem DS, Wilson TG Jr, Higginbottom F, Solnit G. Multicenter retrospective analysis of the ITI implant system used for single-tooth replacements: Preliminary results at 6 or more months of loading. Int J Oral Maxillofac Implants 1997;12:237–242.
5. McGlumphy EA, Mendel DA, Holloway JA. Implant screw mechanics. Dent Clin North Am 1998;42:71–89.
6. Sutter F, Weber HP, Sorenson J, Belser U. The new restorative concept of the ITI dental implant system: Design and engineering. Int J Periodontics Restorative Dent 1993;13: 409–431.
7. Norton MR. An in vitro evaluation of the strength of an internal conical interface compared to a butt joint interface in implant design. Clin Oral Implants Res 1997;8:290–298.
8. Norton MR. Assessment of cold welding properties of the internal conical interface of two commercially available implant systems. J Prosthet Dent 1999;81:159–166.
9. Felton DA. Cemented versus screw-retained implant prostheses: Which is better? [current issues forum]. Int J Oral Maxillofac Implants 1999;14:138–139.
10. Abkowitz S, Burke JJ, Hiltz RH. Titanium in Industry. New York: Van Nostrand Co Inc, 1955.
11. Steinemann SG, Mäusli PA, Szmukler-Moncler S, Semlitzsch M, Pohler O, Hintermann HE, Perren SM. Beta-titanium alloy for surgical implants. In: Froes FH, Caplan I (eds). Titanium '92. Science and Technology. The Minerals, Metals & Materials Society, 1993:2689–2696.
12. Sakaguchi RL, Borgersen SE. Nonlinear contact analysis of preload in dental implant screws. Int J Oral Maxillofac Implants 1995;10:295–302.
13. Burguete RL, Johns RB, King T, Patterson EA. Tightening characteristics for screwed joints in osseointegrated dental implants. J Prosthet Dent 1994;71:592–599.
14. Beitz W. Küttner KH (eds). Dubbel Taschenbuch für den Maschinenbau, ed 18. Berlin: Springer, 1995:G39.
15. Issler L, Ruoss H, Häfele P. Festigkeitslehre: Grundlagen. Berlin: Springer, 1995.
16. Haack JE, Sakaguchi RL, Sun T, Coffey JP. Elongation and preload stress in dental implant abutment screws. Int J Oral Maxillofac Implants 1995;10:529–536.
17. Holmes DC, Haganman CR, Aquilino SA. Deflection of superstructure and stress concentrations in the IMZ implant system. Int J Prosthodont 1994;7:239–246.

COPYRIGHT © 2000 BY QUINTESSENCE PUBLISHING CO, INC. PRINTING OF THIS DOCUMENT IS RESTRICTED TO PERSONAL USE ONLY. NO PART OF THIS ARTICLE MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM WITHOUT WRITTEN PERMISSION FROM THE PUBLISHER.