Three-Dimensional Computerized Stress Analysis of Commercially Pure Titanium and Yttrium–Partially Stabilized Zirconia Implants

Ralf-Joachim Kohal, DMD[a]
George Papavasiliou, DDS, MS, Dr Odont[b]
Phophi Kamposiora, DDS, MS, Dr Odont[b]
Aris Tripodakis, DDS, MS, Dr Odont[c]
Jörg Rudolf Strub, DMD, PhD[d]

Purpose: The purpose of this study was to use three-dimensional finite element analysis to analyze stress distribution patterns in Re-Implant implants made of commercially pure titanium (cpTi) and yttrium–partially stabilized zirconia (YPSZ). **Materials and Methods:** Two three-dimensional finite element analysis models of a maxillary incisor with Re-Implant implants were made, surrounded by cortical and cancellous bone. A porcelain-fused-to-metal crown for the cpTi implant and a ceramic crown for the YPSZ implant were modeled. Stress levels were calculated according to the von Mises criteria. **Results:** Higher stresses were observed at the area where the implant entered the bone. Stresses were higher at the facial and lingual surfaces than the proximal ones. In cortical bone and at the junction of cortical and cancellous bone, stress distribution presented a pattern of alternating higher (4.0 to 5.0 MPa) and lower (1.3 to 2.0 MPa) stress areas. Higher stresses were found at the apical third of the implant-to-bone junction as well. **Conclusion:** Re-Implant implants presented a pattern of low, well-distributed stresses along the entire implant-to-bone interface. YPSZ implants had very similar stress distribution to cpTi implants and may be viable esthetic alternatives, especially in maxillary anterior regions. *Int J Prosthodont 2002;15:189–194.*

Over the last few years, dental rehabilitation with osseointegrated dental implants has become a well-accepted treatment modality. A serious effort is made to create implants that are more "patient friendly," maintaining at the same time the characteristics giving them high success rates.[1–4]

In contrast to the proposed late implant placement 6 to 9 months after the last tooth extraction,[1] researchers now suggest delayed[5] or immediate implant placement.[6–8] The Re-Implant system was created to solve the problem of incongruency between extraction sockets and conventional screw- or cylinder-type implants.[7,9] It is a one-stage root analogue implant system.[10] The titanium implants resemble closely the anatomy of the extraction socket and are custom made by means of a computer-aided design/manufacturing (CAD/CAM) system.[7,9]

Root analogue custom-made implants for immediate placement have several advantages,[9] the major ones being reduced soft tissue trauma and fewer surgical procedures. Histomorphometric analysis of the Re-Implant system was done on monkeys, showing a mean bone-to-implant contact of 41%.[7] Biomechanical analysis by means of an artificial mouth system as well as longitudinal clinical studies are underway for the long-term evaluation of the Re-Implant system.

A new type of Re-Implant implant was created using yttrium–partially stabilized zirconia (YPSZ) ceramic material instead of commercially pure titanium (cpTi) to fabricate the implant. YPSZ implants

[a]Senior Lecturer, Department of Prosthodontics, Albert-Ludwigs-University, Freiburg, Germany; and Clinical Assistant Professor, The University of Texas at Houston, Health Science Center, Division of Periodontics.
[b]Academic Instructor, Department of Fixed Prosthodontics, University of Athens, Greece; and Adjunct Assistant Professor, University of North Carolina at Chapel Hill.
[c]Assistant Professor, Department of Fixed Prosthodontics, University of Athens, Greece.
[d]Professor and Chair, Department of Prosthodontics, Albert-Ludwigs-University, Freiburg, Germany.

Reprint requests: Dr Ralf-Joachim Kohal, Department of Prosthodontics, Albert-Ludwigs-University, Hugstetter Strasse 55, 79106 Freiburg, Germany. Fax: + 49 761/270-4824. e-mail: kohal@uni-freiburg.de

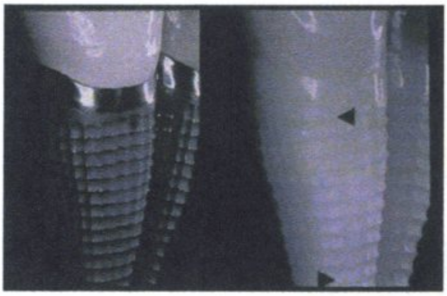


Fig 1 Implant models to be analyzed. *Left:* cpTi implant with porcelain-fused-to-metal crown. *Right:* YPSZ implant with an all-ceramic crown; *arrowheads* = region of the honeycomb surface.

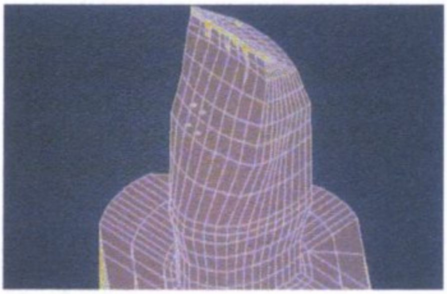


Fig 2 3-D FEA model. The four *arrows* in the center of the palatal surface indicate an area of oblique stress induction.

showed the same amount of osseointegration (52.3%) as the cpTi implants (52.5%) in an animal experiment (Kohal et al 2001, unpublished data). YPSZ is a very strong ceramic material that is used, among others, for the fabrication of all-ceramic posts and cores.[11–17] The new type of implants are restored with cemented YPSZ posts and Empress-1 (Ivoclar) all-ceramic crowns. This all-ceramic implant-post-crown combination offers excellent esthetics that resemble very closely the characteristics of the extracted tooth.

The purpose of this study was to use three-dimensional finite element analysis (FEA) to analyze stress distribution patterns in bone surrounding Re-Implant implants. A secondary purpose was to evaluate whether there are differences in stress distributions for the conventional Re-Implant treatment method, including a titanium implant and post with a metal-ceramic crown, and the all-ceramic Re-Implant method, consisting of a YPSZ implant and post restored with an all-ceramic crown (Empress-1). Our hypothesis was that there are no differences in stress distribution using FEA between the two treatment methods.

Materials and Methods

This study used Cosmos/M, version 1.65 FEA computer software (Structural Research and Analysis). The rationales for the selection and the hardware and software have been previously described.[18,19]

The maxillary incisor was selected because of its simple shape and its likelihood of being subjected to oblique occlusal stresses. Measurements taken from two life-size models of Re-Implant systems (implant-post-crown; Fig 1) were used to develop the model. The model of a maxillary incisor (Fig 2) was constructed in two versions that allowed varying assignment of properties so that all experimental variables could be investigated. One version was a cpTi (grade 2) Re-Implant implant plus titanium post restored with a metal-ceramic crown. The second version was a YPSZ Re-Implant implant plus YPSZ post restored with an all-ceramic (Empress-1) crown. The combination of implant and restorative material was chosen considering that a ceramic crown should restore a ceramic implant for optimum esthetic results. Each model had the maxillary incisor embedded in cortical and cancellous bone. Both versions included modeling for use of glass-ionomer luting cement in a film thickness of 25 µm. Loads of 10 MPa[20] (100 N/mm^2, 10 kg/mm^2) were applied obliquely on the palatal surface at the middle third of the crown. A total of two models with 6,784 elements and 20,444 nodes each were constructed. The element type chosen was a solid, 3-D, eight-node, hexahedral element.

The mechanical property values required for the analysis (modulus of elasticity, E, Poisson's ratio, v) were taken from previously published data[21,22] (Table 1). In this study, the boundary conditions chosen were as follows. All models were assumed to be 50% osseointegrated. Selected areas on the bottom half of the bone surrounding the implants were fixed for all degrees of freedom to stabilize the model in space. The three rotational degrees of freedom for all nodes in each model were also fixed. This was a requirement of the type of stress analysis performed. Key regions were selected within the bone-to-implant junction for comparisons among models. The regions were: *(1)* the level where the implant enters the cortical bone, *(2)* within the cortical bone, *(3)* the cortical-to-cancellous bone junction, and *(4)* the apical third of the implant-to-bone junction. Comparisons were also done for the two different prosthetic posts and crowns. Stress levels were calculated according to the von Mises criteria.[23]

Results were displayed as stress contour plots to indicate regions of maximum stress concentration. Statistical analyses have only rare applications in computer-simulated FEA studies. Repetitive calculations were unnecessary since computer model results were invariant.[24]

Results

Stress outcomes for both crowns were very similar, so only one of them is shown (Fig 3). There was high stress concentration at the area of load application. More stress was distributed to the palatal surface and very little was transmitted labially, while reduction was evident in a lesser degree toward the margins of the crowns. At the labial and palatal surfaces of the margins, the stress pattern was inverted, resulting in high stress concentration (Fig 3). Stress levels and distribution at the surfaces of the posts were very similar to those at the surface of the crowns, showing that stresses were transmitted in full through the bodies of the crowns and to the posts (Fig 4). There were no differences in stress distributions for the posts in the two treatment groups.

Results for the implants and the surrounding bone are presented together, with emphasis given to the bone-implant interface. Figure 5 shows a 3-D close-up view of the region where the implant enters the cortical bone. For both models, stresses were highest at the area where the implant entered the bone (4.5 MPa). Stresses were also higher at the facial and lingual surfaces compared to the proximal ones (1.3 to 2.0 MPa). There was a considerable drop of stress levels moving outward into the bone, even within the first millimeter (two-element width; Fig 5).

For regions 2 and 3 (within cortical bone and at the cortical-cancellous bone junction) and for both models, stress distribution presented a pattern of alternating high- and low-stress areas. High-stress areas (4.0 to 5.0 MPa) coincided with the outside edges of the honeycomb surface (Fig 1). Lower stress areas (1.3 to 2.0 MPa) were within the confines of the concave areas of the honeycomb surface.

High stresses were found in region 4 (apical third of implant-to-bone junction) and were similar for both implant models (Fig 4). Higher stresses (4.0 to 5.0 MPa) were distributed on the facial and lingual surfaces. On the proximal surfaces, stresses were lower (1.0 to 1.5 MPa). The alternating pattern was not present in these regions.

Discussion

FEA of models of both types of Re-Implant implants led to some interesting observations regarding the stress distribution patterns. Stresses for both crowns and posts (metal post/metal-ceramic crown, ceramic post/ceramic crown) were very similar. This observation is logical, since all materials involved in that area have very similar Young's moduli (Ti ≈ 100 GPa; YPSZ ≈ 200 GPa). It was shown in a previous study[24] that unless the Young's moduli among materials do not differ more than five- to sevenfold, stress levels and distributions are similar for the materials. An important observation is the inversion of the stress distribution at the margins of the posts and the crowns. The reason is that the flexural center of the system is located at and below the margins, and high tensile and compressional stresses are created along the direction of the applied force (palatolabially).

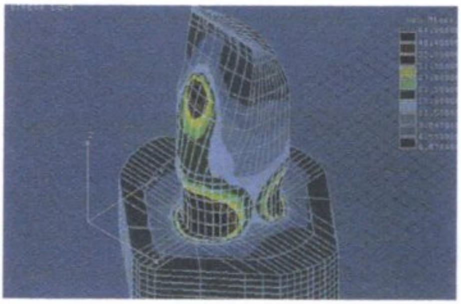
For both implant types, outcome stress levels were low (< 5.0 MPa). Higher stresses were concentrated along the facial and lingual surfaces of the junction all the way to the apex. Cylindric implants without a macrosurface pattern similar to the one of the Re-Implant implants show high stress concentration at the area where the implant enters the bone,[21] but stress is reduced considerably within the first millimeters of cancellous bone. Screw-type cylindric implants[22] show a wider band of stress concentration from the crown to the apex, which does not reach the bottom of the implant.

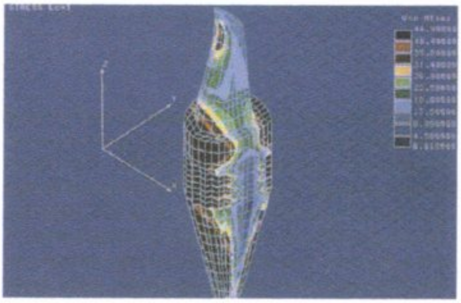
Distribution of stress over a wider surface is favorable, as more bone surface withstands occlusal forces. The form of the Re-Implant implant copies the root of the extracted tooth. The root form leads to more apical distribution of stress. The honeycomb surface pattern might affect the stress distribution as well. It increases the surface area where stress is distributed. Furthermore, the edges of the honeycomb surface concentrated stresses, while the concave areas were more protected.

Table 1 Assumptions for the FEA Model

	Young's modulus (MPa)	Poisson's ratio
Hard tissue bulk properties		
Cortical bone[46]	10,000	0.30
Cancellous bone[46]	250	0.30
Crown and implant material bulk properties		
Au alloy[47]	86,200	0.33
Ti grade 2–4[48]	102,194	0.35
Porcelain[49]	82,800	0.35
Empress-1*	100,000	0.28
YPSZ*	200,000	0.35
Dental cement		
Glass-ionomer[50]	7,560	0.35

*According to manufacturer.





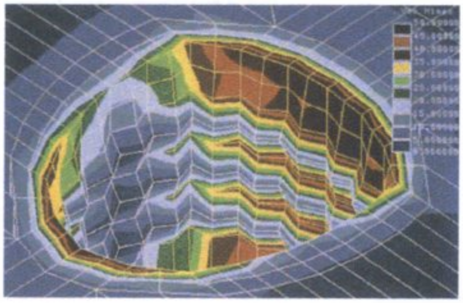


Fig 3 *(left)* 3-D stress plots of restoration (all-ceramic system). The stress plot was similar for the cpTi implant restored with a metal-ceramic crown and the YPSZ implant restored with an Empress-1 crown.

Fig 4 *(below left)* 3-D stress plots of implant-post combinations (all-ceramic system). The stress plots were identical for the two models. For this plot, the bone was removed from around the implant.

Fig 5 *(below)* 3-D stress plots of implant-bone interfaces (all-ceramic system). For better visualization of the outcome, the implants were removed from the plots. The plots were similar for the two different models.

Since the expectations regarding esthetics in dentistry are growing,[25] research in the field of all-ceramic materials for restoration of the natural dentition and dental implants was intensified.[26–33] Although the crown that abuts the implant may be esthetically optimal, the possibility exists that the grayish color of the titanium implant shines through the thin peri-implant mucosa, thus impairing the entire esthetic result.[33–35] A ceramic implant could solve these esthetic problems, especially in the anterior region. The ceramic implants used so far (Crystalline Bone Screw[36], Sandhaus, and the Tübingen implant[37,38], Friadent) are too brittle and prone to fracture. Their clinical long-term results are questionable.

The high-performance ceramic zirconia was evaluated regarding its use as a dental implant material.[39–41] Zirconium dioxide is very stable[12,41] and highly biocompatible.[42,43] It is used in the fields of orthopedics[44] and dentistry.[11,13–16,45] Re-Implant implants modeled to be made of YPSZ showed low, well-distributed, favorable stress distribution patterns similar to those of titanium implants and can be characterized as favorable or nondestructive. Stress values were similar for both models for all regions.

FEA is a basic research tool and is widely used in engineering and the automotive and aeronautic industries. In these areas, the material properties can be calculated with precision, and most of the variables can be controlled. In bioengineering, however, where we are dealing with biologic structures (bone, soft tissues), the physical properties of these structures are only approximations, since all materials are considered to be homogeneous and have a linear response to stress. However, in a living organism, the response of these structures to stresses is more complex, and the accuracy of a 3-D FEA relies on the precision of the simulation model. In conclusion, the presented results were obtained from a simulated model from which biologic variabilities may occur. In dentistry, FEA, like any other basic research method, is used as an initial step and an aid for planning further laboratory tests and clinical projects that will reduce inaccuracies inherent with the FEA method. Clinical projects also have to show the longevity and success rates of Re-Implant implants.

Conclusions

Under the limitations of the FEA method, the following conclusions can be made:

1. There are no important differences in resolved stresses between the two different implant-post-crown combinations.
2. Re-Implant root analogue implants present a favorable stress distribution at the bone-to-implant junction.
3. YPSZ implants have stress distribution similar to cpTi implants and may be a viable alternative, especially for esthetic regions.

Acknowledgment

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Literature Abstract

Maxillary bone grafting for insertion of endosseous implants: Results after 12–124 months.

This study aimed to evaluate the long-term clinical and radiographic results of grafting the maxillary sinus with autogenous bone grafts. An assessment of patient satisfaction was also done using a questionnaire; 99 patients were studied. The mean alveolar bone height between the maxillary sinus and the oral cavity was 3 ± 2 mm as measured on an orthopantomogram. Bone grafts were harvested from the iliac crest (83 patients, 162 sinuses, 353 implants), the mandibular symphysis (14 patients, 18 sinuses, 37 implants), or the maxillary tuberosity (two patients, two sinuses, two implants). In 74 patients, bone grafting and implant placement were done in a two-stage procedure when the height and /or width of the alveolar bone was less than 5 mm. The other 25 patients underwent a one-stage procedure where bone grafting and implant placement were performed simultaneously. There were 72 patients restored with implant-supported overdentures and 27 patients restored with fixed partial dentures. The implant survival rate in this study was 91.8% (32 of 392 implants had to be removed). The survival rate of the implants between the one-stage and two-stage procedures did not show any significant difference. There was no significant difference in the implant survival rates between the iliac crest and mandibular symphysis bone grafts. Patient assessment of their prosthetic reconstructions showed that they were overall satisfied with the results. The authors conclude that maxillary sinus augmentation with autogenous bone grafts for implant placement is reliable, with good long-term results.

Raghoebar GM, Timmenga NM, Reintsema H, Stegenga B, Vissink A. *Clin Oral Implants Res* 2001;12:279–286. **References:** 39. **Reprints:** Dr Gerry M. Raghoebar, Department of Oral and Maxillofacial Surgery and Maxillofacial Prosthetics, University Hospital Gröningen, PO Box 30.001, 9700 RB Gröningen, The Netherlands—*Swee-Chian Tan, Iowa City, Iowa*