Three-Dimensional Finite Element Analysis of Stress Distribution in Zirconia and Titanium Dental Implants

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Zirconia has been presented as an alternative biomaterial to titanium, commercially presented as a single-body implant and/or as an abutment, demonstrating clinically biocompatible favorable results in white and rose esthetics. However, the number of long-term in vivo studies and mechanical tests evaluating the response of stress distribution compared with titanium implants is still limited. The aim of the study was to compare the principal peak stresses in the peri-implant bone around titanium and zirconia implants using the finite element method. Four groups of 3-dimensional models were constructed for the tests: G1, external hexagon titanium implant with a zirconia abutment; G2, zirconia implant with a zirconia abutment; G3, single-body titanium implant; and G4, single-body zirconia implant. Axial and oblique loads of 100 N at 45° were simulated in the prosthetic crown. The bone results showed that the peak stresses decreased by 12% in zirconia implants with 2 parts for axial load and 30% for the oblique load. In single-body implants, the peak stresses decreased 12% in the axial load and 34% in the oblique load when a zirconia implant was used compared with a titanium implant. Although the stress values in megapascals are similar, it can be concluded that the zirconia implants decrease the stress peaks at the peri-implant bone area around the implant platform when compared with titanium implants.

Key Words: dental implantation, dentistry, engineering, finite element analysis, prostheses and implants, engineering, dental implantation, research, dentistry

INTRODUCTION

The ideal material for the manufacture of dental implants must have biocompatibility, appropriate hardness, corrosion resistance, and wear and fracture strength.[1,2] Today, most dental implants are made of titanium, considered the gold standard material because of its characteristics, excellent biocompatibility, and long-term clinical success.[1,3]

Despite the popularity of titanium, allergies to this material have been reported (estimated prevalence of 0.6%). The induction of hypersensitivity in sensitive patients was described as a possible etiologic factor for implant failure. The demand for metal-free treatments has also grown recently.[2,4]

Thus, in recent years, zirconia dental implants have emerged as an alternative to titanium implants. Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) shows improved properties that make it a suitable material for the manufacturing of dental implants.[5] It stands out from other ceramics because of its high corrosion and wear resistance and its high flexural strength (900–1400 MPa) and hardness of greater than 10 Mpa/m0.5.[6,7] A unique characteristic of Y-TZP is transformation toughening that causes a phase transformation, generating an expansion of the local volume, limiting the crack propagation of the material.[6,8]

Studies in animals have demonstrated success in osseointegration of zirconia implants, indicating an average bone-to-implant contact greater than 66%[9,10] and having osseointegration characteristics similar to that of titanium implants.[11] Zirconia osteoinduction properties have been demonstrated to promote osteoblast proliferation.[12,13] Osteoconductive characteristics were also identified, orienting the size and alignment of osteoblasts.[14] A recent systematic review found no statistically significant differences in the values of torque removal between titanium and zirconia implants in animal studies.[15] The soft-tissue reaction in contact with zirconia oxide discs has shown similar or better results compared with titanium, with better healing response, reduced plaque adhesion, and less inflammatory infiltrate.[16,17]

Case reports, case series, prospective clinical and randomized clinical trials with up to 5 years of follow-up have shown

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satisfactory results of zirconia implants maintaining peri-implant tissues and esthetics,[18–22] comparable to titanium implants.[19,23–25] Zirconia implants have achieved survival rates similar to those of titanium implants, achieving healthy and stable hard and soft tissues in partially toothed patients.[26,27] Nevertheless, other studies have shown evidence of increased bone loss after the first year.[28,29]

The number of studies evaluating load response and the stress distribution patterns of zirconia implants compared with titanium implants are still limited. Different methods have been used to study the forces on prosthesis and on oral cavity tissues.[30] During the past 30 years, the finite element analysis (FEA) method has become an increasingly useful tool for predicting the effects of stress on implants and the surrounding bone,[31–35] a key factor related to the long-term success of dental implants that could be the result of different aspects, such as loading modality, prosthetic platform, surface and geometrics of implants, and the characteristics of the surrounding bone.[35,36] FEA allows an analytical evaluation of the distribution of tensional forces through a mathematical virtual model that includes the aforementioned variables in order to offer directions to the clinician on the most favorable choice.[30,36,37]

Therefore, the aim of the present study was to evaluate the tensile and compressive stress in the peri-implant bone around titanium and zirconium implants using 3-dimensional (3D) FEA.

MATERIALS AND METHODS

To perform the tests using the FEA method, a computer-aided design software (SolidWorks 2011, Dassault Systemes, SolidWorks Corps, Waltham, Mass) was initially used to build 3D models of 2 types of single-unit implants. The first comprises a cylindrical threaded implant with an external hexagon-type connection, 10 mm in height, with a 4.1-mm diameter platform (Figure 1a) together with a customized abutment with an upper conical portion (Figure 1b) and a titanium bolt screw with threads in only the lower third (Figure 1c). The second solid implant was shaped exactly alike with a connector; however, the implant and connector are represented by a single body, as shown in Figure 2.

The editing of the digital model of the prosthetic crown is initially performed by a computerized tomography (CT) scan examination covering the mandible region in cross sections of 0.25-mm distance for a total of 212 slices. These slices were recorded in DICOM format (Digital Imaging and Communications in Standard Medicine) and imported into InVesalius 3.0 image-processing software (Information Technology Center, Renato Archer, Campinas, SP, Brazil) to subsequently obtain a digital reconstruction of the mandible in a 3D model (Figure 3a). In all, for the dental element 35, only the crown was retained to provide the shape and size of the final prosthetic crown (Figure 3b).

The prosthetic crown was modeled and edited into 2 parts: first, a crown with feldspathic porcelain covering the infrastructure in zirconia with at least 0.5-mm thickness, similar to the ceramic crown. Between the crown and the customized abutment, a thin structure of approximately 0.1 mm was configured, simulating zinc phosphate cement. For the FEA, a layer of cement was used as an ANSYS bonded contact. Cortical bone of 1.0-mm thickness covering the medullary bone (Figure 4) and 3 enamel cylinders were distributed on the occlusal surface of the prosthetic crown to simulate the occlusal contacts (Figure 5).

After the virtual reconstruction, the models were exported to the ANSYS software for editing the models and configuration in relation to the mechanical properties according to their elastic modulus and Poisson's ratio, in accordance with the literature (Table 1).

Rigid supports were added in the lower and lateral bone regions, simulating the model union to the rest of a mandible. All contacts were considered as bonded. Vertical loads parallel to the long axis of the tooth with 100-N magnitudes were equally distributed between the enamel structures and were added in the enamel cylinders as the first load condition (Figure 6a). As a second condition, an oblique load of 45° to the long axis of the tooth was simulated in the central enamel structure, as shown in Figure 6b.

Discretization was carried out, that is, the model transformation process in nodes and elements required to carry out the simulation. Meshes referred to as "finite elements" were generated and validated by a mesh-refining process, verifying the convergence of the results. The number of nodes and elements was gradually increased until the difference in peak stresses between one mesh refinement and another was 5% or less. Thus, the geometric error characteristic of a mesh discretization process was minimized. The mesh was generated with quadratic tetrahedral elements of 10 nodes (solid 187), providing a suitable copy of irregular geometries, as shown in Figure 7. All models were then solved (Windows XP X64, Intel Core 2 Quad Q6600 processor, 8 Gb memory RAM). Graphical and numerical plots of the data were recorded, evaluated, and compared for analysis of qualitative and quantitative results in percentages.

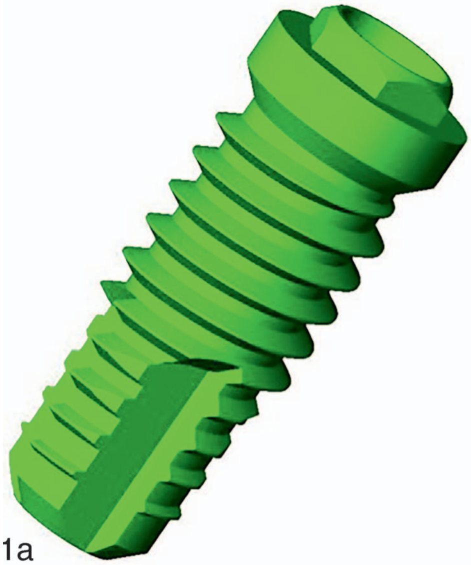
RESULTS

Considering that each output may have an error of accuracy of up to 5%, they were analyzed according to the value of the stress peaks for each model for each load range (Table 2).

Regarding the stress peaks for axial load, the highest tensile stress between the groups was for G2 and compression for G1; regarding the oblique load, the greatest tensile stress was for G1 and compression for G3. The arithmetic average between the stress and compression values was performed for each load, recording the percentage for each group (Figure 8).

In general, G1 exhibited the highest principal stress and G4 the lowest, showing a decrease of 23% in axial load and 31% in oblique load. G2 presented lower stress than G1, and a difference of 12% in axial load and 30% in oblique load were found. During an axial or oblique load, the lowest stress was found in the zirconium implants for groups G2 and G4. However, the 1-piece zirconia implant (G4) presented lower stresses than the 2-piece zirconia implant (G2).

In accordance with the average percentage values, the results showed that for the axial load (Figure 9), the titanium implant group with the zirconia abutment (G1; 100%) presented the highest stresses compared with the other groups



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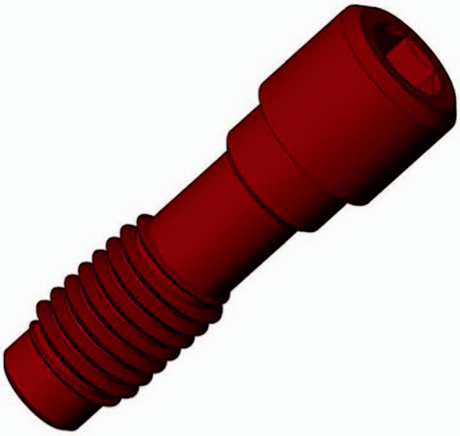

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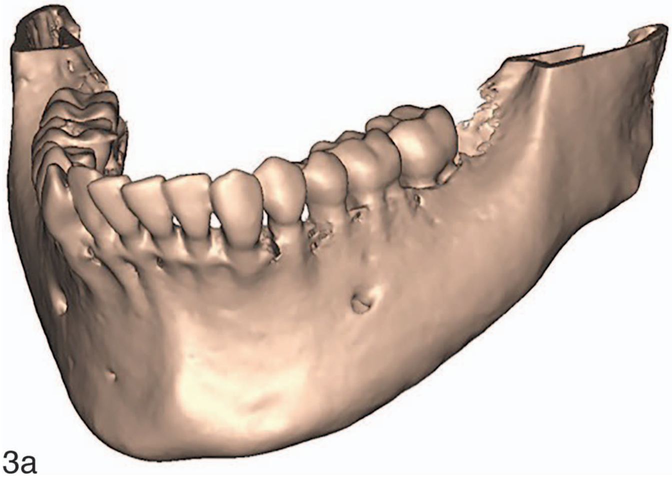

3a

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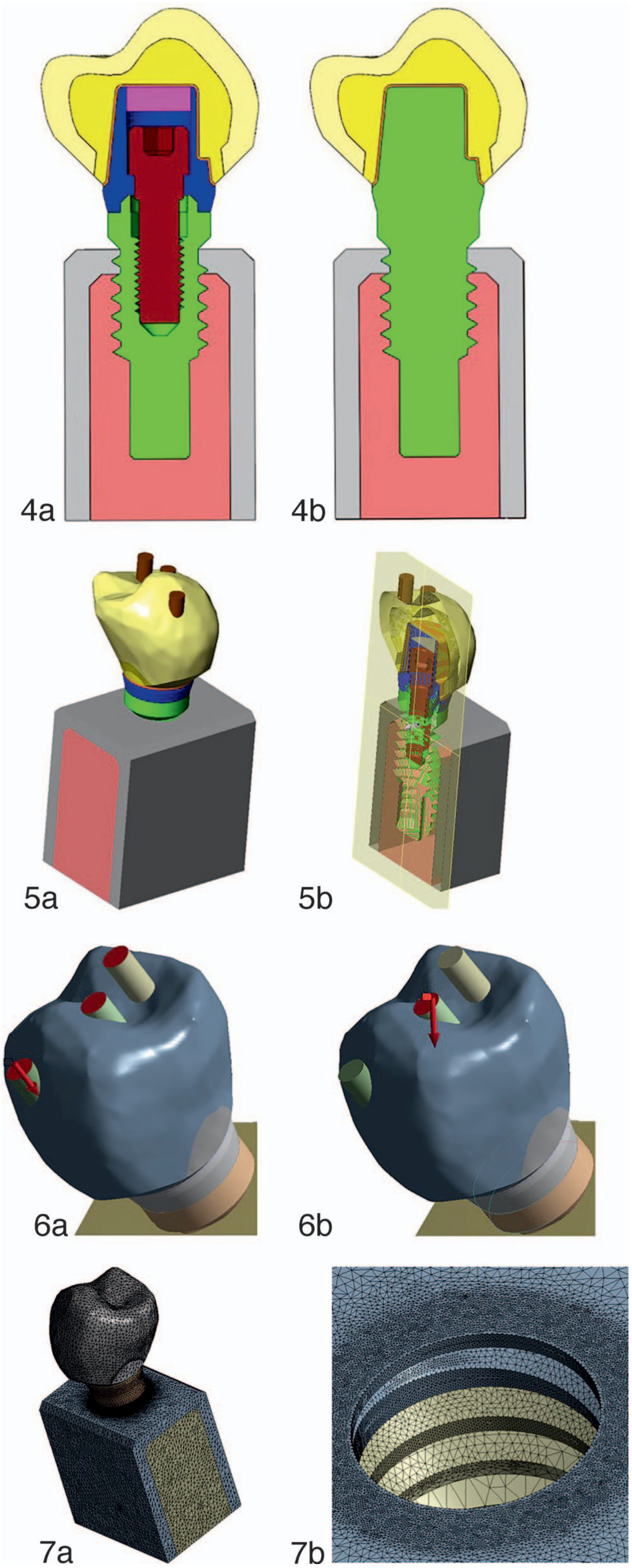
Figures 1–3. Figure 1. Three-dimensional model of external hexagon implant (a), customized abutment (b), and bolt screw (c). **Figure 2.** Three-dimensional model of the single-body implant. **Figure 3.** Digital reconstruction from computerized tomography scan without any editing (a). Dental element 35 was stored and subsequently sectioned in its cervical region to provide the shape and size of the final prosthetic crown (b).



FIGURES 4–7. FIGURE 4. Figure of final models; external hexagon implant (a) and single-body implant (b). A cut-away view shows medullary bone (pink), cortical bone (gray), implant (green), screw (brown), connector (blue), gutta percha (purple), zinc phosphate cement (orange), infrastructure (dark yellow), and ceramic (light yellow). **FIGURE 5.** Three enamel cylinders were distributed on the occlusal surface of the prosthetic crown (a–b) to simulate occlusion contacts. **FIGURE 6.** Vertical load parallel to the long axis (a), oblique loading of 45° to the long axis of the tooth (b). **FIGURE 7.** Resulting mesh of finite elements in external view (a) and internal view (b). The results of elements for the model with the HE implant was 1 007 028 nodes and 617 222 and 1 338 505 nodes and 869 393 for elements with the single-body models.

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(G2, 88%; G3, 89%; G4, 77%). The stress decreased 12% in the zirconia implants with a zirconia abutment in G2 compared with G1, 11% in G3, and 34% in G4. Comparing single-body implants, the stress decreased 12% when using a zirconia implant (G4) compared with a titanium implant (G3).

During the oblique load (Figure 10), the titanium implant group with the zirconia abutment (G1) and the single-body titanium implant (G3) exhibited the highest stresses, 77% and 100%, respectively, when compared with the other groups (G2, 67%; G4, 66%). The stresses decreased 30% in the zirconia implants with a zirconia abutment (G2) compared with the titanium implant with a zirconia abutment (G1). For single-body implants, the stress decreased 34% when the zirconia implant was used compared with the titanium implant.

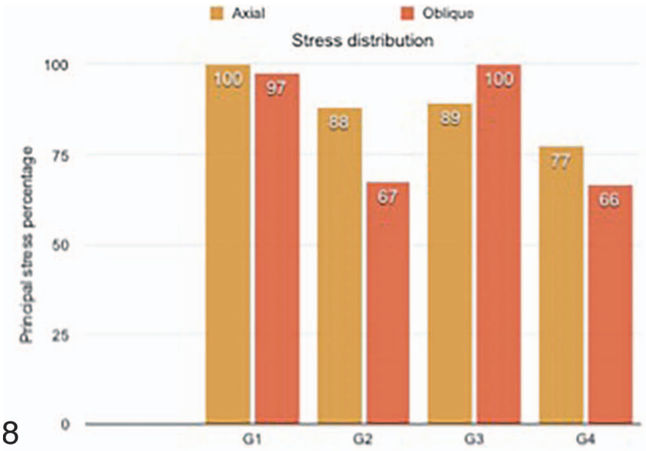
DISCUSSION

The present study was designed to evaluate the tensile and compressive stress in titanium and zirconium implants using the 3D FEA. The FEA allows the handling of complex structures and the material's variables, qualitatively calculating the biomechanical behavior expected in clinical reality. To improve the accuracy of the FEA, the present study maintained the simulation model's details and physico-mechanical characteristics; nevertheless, there is awareness of possible biological variations.

The long-term success of implant treatment is related to the stress distribution of the surrounding tissues. Bone resorption appears to be a biomechanical adaptation or overload related.[42,43] Studies have shown that there is higher stress on the cortical bone[44,45] where the implant enters the bone or on the neck of 1-piece implants.[31,34] Considering the fact that the external hexagon installation is at the preconized bone level, the stress was measured at this level.[46]

The implant-abutment variations of the groups considered in the present study are commonly used in clinical practice. Despite the fact that titanium implants are the gold standard and titanium abutments are the most used, they were not included as a group but are considered in this discussion.

Group 1 (titanium implant and zirconia abutment) broadly presents the highest stress. In vitro studies display a "fretting wear" on the external hexagon system when a dynamic load is applied. The metal becomes abraded in contact with the ceramic, the implant and abutment move closer, and the micro gaps are smaller than in groups with titanium abutments.[47–49] Stimmelmayr and colleagues[50] reported damage to the surface of titanium implants after cyclical loading. Tattoo associated with zirconia abutment are shown in the literature and override the esthetic and biological desired benefits.[51] However, Zembic et al[52] concluded that patients after 3 years with zirconia or



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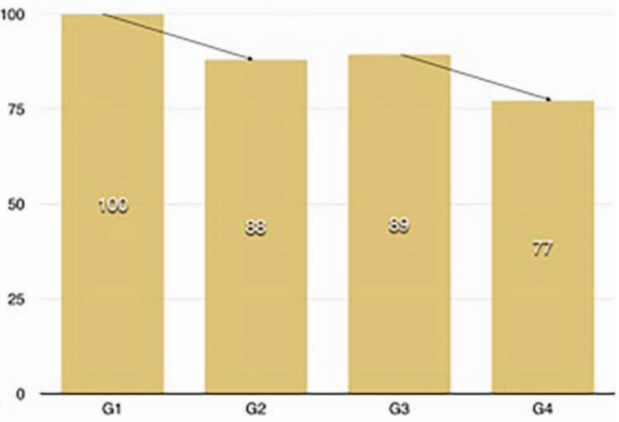

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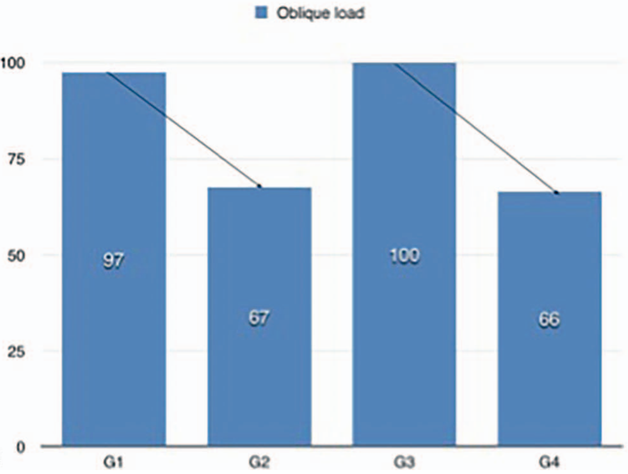

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Figures 8–10. Figure 8. For both loads, the average percentage of stresses decreased for the zirconia implants. **Figure 9**. Results of average percentage values for axial load. **Figure 10.** Results of average percentage values for axial load.

titanium abutments exhibited the same survival, technical, biological, and esthetic outcomes.

An in vitro study exhibited that 2-piece cemented zirconia has an irreparable fracture of the implant head, whereas the weak link in the titanium group was the screw. As a result, 2-piece zirconia implants with a screw connection are proposed as group 2. A stress decrease is observed compared with group 1 (axial: 22%; oblique: 30%), and this fact can be explained by the different Young modulus of the materials.[53]

Group 4 (1-piece zirconia), in general, had the lowest results in both loads. The FEA was performed on the anterior maxillary region and concluded that 1-piece zirconia implants have lower stresses compared with titanium implants with titanium or zirconia abutments, except for tensile stresses under oblique loading. The last disagreement is attributed to different study designs.[32]

The 1-piece zirconia group (G4) showed lower stress values than the 1-piece titanium group (G3). Another FEA study evaluated the stress in the peri-implant bone and implants used to support maxillary overdentures, concluding that 1-piece zirconia may be a potential alternative to conventional titanium implants for this prosthesis.[34] A randomized clinical

Table 1

Mechanical properties

Material	Young Modulus, MPa	Poisson Ratio, MPa
Cortical bone[38]	13 700	0.3
Medullar bone[38]	1370	0.3
Zinc phosphate cement[38]	22 400	0.25
Guta percha[38]	0.69	0.45
Feldspatic porcelain[39]	69 000	0.3
Titanium[39]	110 000	0.35
Zircônia YPSZ[40]	200 000	0.33
In ceram Zircônia[41]	205 000	0.22

Table 2

Results according to the principal stresses (MPa)

Group	Tensile Axial Load	Compression	Tensile Oblique Load	Compression
G1	38.42	58.66	265.75	338.55
G2	40.32	45.01	175.7	242.62
G3	32.20	54.45	259.14	360.91
G4	34.01	40.90	164.29	247.33

trial evaluated 24 patients in a 1-year follow-up with overdentures on 1-piece titanium or zirconia implants. There was no significant difference in the survival rate between the 2-implant groups, but the titanium group presented statistically significant less marginal bone loss.[42] The present study found that groups with zirconia implants (G2 and G4) showed low stress values, in agreement with another FEA study.

Conclusion

Although the stress values in MPa are similar, it can be concluded that zirconia implants decrease the stress peaks in the peri-implant bone when compared with titanium implants.

Considering the study design, it is suggested that zirconium may be an encouraging and potential alternative material for implant treatment, with improved stress distribution evaluated in the FEA. Nevertheless, long-term clinical studies are necessary to support this assumption.

Abbreviations

CT: computerized tomography
DICOM: Digital Imaging and Communications in Standard Medicine
FEA: finite element analysis
HE: external hexagon system implant
Y-TZP: yttria-stabilized tetragonal zirconia polycrystal

Note

The authors declared no conflicts of interest.

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