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Bahattin Saz, Ozgun Yusuf Ozyilmaz & Ozge Doganay Ozyilmaz

Title Page

Stress Distribution in Titanium and Zirconia Implants with Full-Arch Prostheses: A Finite Element Analysis

Bahattin Saz [a], Ozgun Yusuf Ozyilmaz [b], Ozge Doganay Ozyilmaz [c]

[a] Doctoral Student, Department of Oral and Maxillofacial Surgery, Institute of Health Sciences, Bezmialem Vakif University, Istanbul, Türkiye

[b] Professor and Department Head, Department of Prosthodontics, Faculty of Dentistry, Istanbul Galata University, Istanbul, Türkiye

[c] Associate Professor, Faculty of Dentistry, Department of Oral and Maxillofacial Surgery, Bezmialem Vakif University, Istanbul, Türkiye

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Corresponding author

Bahattin Saz, DDS,

Doctoral Student, Department of Oral and Maxillofacial Surgery

Institute of Health Sciences, Bezmialem Vakif University

Adnan Menderes Bulvarı, Vatan Caddesi, Fatih 34093, Istanbul, Türkiye

Phone: +90 506 678 0538   E-mail: bahattinsaz@gmail.com

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Abstract

Objective:

The stress distribution and mechanical properties of materials used in dental implants are critically important for implant success and long-term stability. The aim of this study was to evaluate the stress distribution on implant, prosthetic system, and peri-implant tissues when titanium and zirconia implants are used with different framework materials using three-dimensional finite element analysis (FEA).

Methods:

A three-dimensional edentulous maxilla model was reconstructed from computed tomography data, and twelve finite element models were subsequently developed based on this anatomy to represent different implant and framework configurations. Within the scope of the study, titanium and zirconia implants were modeled in combination with cantilevered and noncantilevered prosthesis types and Co-Cr, PEKK, and zirconium framework materials. An oblique static load of 200 N was applied at a 45° angle in the palato-buccal direction to the central fossa of the first molar on the models. The Von Mises and principal stress distributions in the implant, abutment, screw, framework, and peri-implant bone were examined.

Results:

The highest Von Mises value was recorded in the cantilevered PEKK framework zirconia implant model (378.388 MPa). Compared with the Co-Cr and zirconium framework, the PEKK framework resulted in higher Von Mises stresses and greater prosthesis displacement. The presence of a cantilever increased stress levels in all framework materials, and stress concentrations were observed particularly in posterior abutments and peri-implant bone. Furthermore, stress values in trabecular bone were recorded above the physiological threshold level in the cantilevered PEKK framework models.

Conclusions:

Although zirconia implants exhibited greater stress than titanium implants, they remained within safe limits. Rigid framework materials and cantilever-free designs provide more balanced biomechanical results.

Keywords:

Zirconia implant, Full-arch prosthesis, Stress distribution, Cantilever, Zirconium/PEKK/Co-Cr framework, Finite element analysis

1.INTRODUCTION

Tooth loss can negatively impact an individual's quality of life by impairing function, phonation, and aesthetics. Endosseous implants, which are frequently used in clinical dental practice, are widely employed in the treatment of tooth loss [1,2]. Titanium-aluminum-vanadium alloy (Ti-6Al-4V) is widely preferred in dental implant production due to its high mechanical strength, low density, and resistance to corrosion in physiological environments [3]. Titanium implants have been used in clinical practice for many years, with high success rates. However, bacterial colonization around the implant can lead to infection in the early stages and, in later stages, inflammation in the peri-implant tissues and resorption of the surrounding bone, resulting in implant loss [4,5]. In addition, titanium metal allergy, which is rare but can occur in some individuals, raises questions about its biocompatibility [6,7]. Furthermore, issues related to the material's wear resistance and surface stability have been reported with long-term use; it has been noted that ions released through wear and corrosion processes can enter the systemic circulation and pose various biological risks [8,9]. These disadvantages have accelerated the search for alternative biocompatible materials for use in dental implants [10].

Zirconia implants are typically made from yttria-stabilized tetragonal zirconia polycrystal (Y-TZP)-based ceramic materials, sometimes with a small amount of alumina added, and have been developed as alternatives to titanium implants. Zirconium oxide stands out in animal and in vitro models for its high biocompatibility, low bacterial colonization potential, aesthetic properties, and corrosion resistance; compared with titanium, it has also been shown to be associated with less biofilm accumulation, bone resorption, and inflammatory response [11,12].Because zirconium does not dissolve in environments such as saliva, sweat, and acid owing to the stable oxide layer formed on its surface, ions are not released into circulation. This property, along with its high corrosion resistance, biocompatibility, high hardness, and wear resistance, makes it a strong biological and mechanical alternative in implantology [13,14]. The framework materials used in implant-supported prostheses play a decisive role in biomechanical performance and long-term stability [15]. The literature reports that cobalt-chromium, zirconium, and PEKK offer different biomechanical and clinical advantages in their use in implant-supported fixed prostheses. The resistance of cobalt-chromium to deformation and its reliable mechanical performance; the high biocompatibility, reduced plaque accumulation, and aesthetic properties of zirconium; and the high pressure resistance, shock absorption capacity, and bone-like elastic modulus of PEKK are among the main features that distinguish these materials [15–18].

Three-dimensional finite element analysis (FEA) is an effective computational method that allows the evaluation of stress distributions caused by different design parameters and prosthetic components in dental implant systems. It is widely used in the analysis of load transfer mechanisms that cannot be directly observed clinically and is an important tool, particularly for predicting the mechanical performance of new materials under intraoral loads [19,20].

This study aimed to evaluate the effects of titanium and zirconia implants using different framework materials on the stress distribution in the implant, prosthetic system, and peri-implant tissues via three-dimensional finite element analysis (FEA).

2.MATERIALS AND METHODS

This study was supported by the Bezmialem Vakif University Scientific Research Projects Coordination Unit (Project No: 2023/1210). A three-dimensional (3D) model of an edentulous maxilla was created using computed tomography (CT) data obtained from an adult patient. The CT data were processed using 3DSlicer software and converted to stereolithography (STL) format. Reverse engineering processes were performed using Blender software; preparation for finite element analysis (FEA) and optimization of the mesh structure were achieved using ALTAIR Hypermesh. Model solutions were completed using the ALTAIR OptiStruct (ALTAIR, Troy, MI, USA) solver. Visible Human Project data were used as a basis for bone modeling, and cortical and cancellous bone structures were modeled separately. The internal bone structure was created with a defined cortical thickness of 1 mm, and the internal volume was filled with trabecular bone.

Within the scope of the mechanical analysis, models were created, and analyses were performed using two different implant materials, titanium and zirconia; two prosthesis types, cantilevered and non-cantilevered designs; and three different framework materials, Cr-Co, PEKK, and zirconium. (Table 1). The Toronto-type prosthesis framework material and monolithic zirconia were preferred in all models.

Table 1. Implant Groups, Nodes and elements

Three-dimensional digital models of the Neodent Zi (4.3 × 10 mm) zirconia and Straumann BLT (4.1 × 10 mm) titanium implant systems were designed in a computer-aided design (CAD) environment based on the manufacturers' catalog specifications. Each implant assembly, comprising 30-degree angled and straight multiunit abutments with occlusal screws, was modeled with high geometric fidelity to ensure accurate representation for finite element analysis (Fig. 1).

Fig. 1. Three-dimensional computer-generated models of titanium and zirconia implants (converted into STL format) used for finite element simulations

A total of four implants were used in the cantilevered system, with the anterior implants placed vertically and the posterior implants placed at a 30° angle. In the noncantilevered system, a total of six implants were placed, with the implants in the lateral incisor, first premolar, and first molar regions positioned vertically (Fig. 2). The detailed group configurations are presented in Table 3.

Fig. 2. Schematic representation of implant-supported full-arch designs: (A) four implants with distal cantilever extensions; (B) six implants without cantilever extensions

The tooth dimensions in the superstructure were determined using Wheeler’s Dental Anatomy Atlas as a reference, and the modeling was performed using Blender software. A detailed list of all components used in the study is presented in Table 2 [48].

Table 2. Details of all implant and prosthetic component

Under loading conditions, an oblique static force of 200 N was applied at a 45° angle in the palato-buccal direction to the central fossa of the first molar tooth (Fig. 3). The implant–bone interface was modeled assuming full osseointegration, and the connections between the prosthesis components were considered rigid.

Fig. 3. Applied oblique loading (A), boundary conditions (B), and representative finite element mesh (C) of the finite element model.

All analyses related to the structural and mechanical characterization of zirconia implants were performed at the Metallurgy and Materials Engineering Laboratory of Marmara University. Microstructure examinations were conducted using scanning electron microscopy (SEM; Thermo Scientific, Quattro S**),** and the elemental compositions were analyzed using energy-dispersive X-ray spectroscopy (EDX; integrated with the same SEM system). X-ray diffraction (XRD; Rigaku MiniFlex) was used to determine phase compositions, while mechanical properties were evaluated using nanoindentation tests, and Young's modulus and Poisson's ratio were determined. The elastic modulus, Poisson's ratio, and Young's modulus values of all materials used are summarized in Table 3 .

Table 3. Mechanical properties of all materials

The von Mises stress criterion is widely used for predicting possible mechanical failure in ductile materials. Within the scope of FEA, the von Mises stress values for different framework materials with implants, abutments, and connecting screws were calculated. In addition, the maximum and minimum principal stresses formed in cortical and trabecular bone and the displacement amounts in the prosthesis structure were analyzed.

3.RESULTS

The stress values were found to be higher in all groups except for the occlusal screw in ceramic implants than in titanium implants (Table 4). The highest von Mises value among all models was observed in the PEKK framework model with zirconia implants and a cantilever, which was calculated as 378.388 MPa (Table 4). In the groups in which the PEKK material was used, the von Mises stress values of the framework were lower than those of the Co-Cr and zirconium framework materials.

The lowest von Mises stress value observed in the implants (96,101 MPa) was found in the model using a titanium implant, without a cantilever, and with a Co-Cr framework material. The next lowest von Mises stress value was observed in the same type of model containing a zirconium framework (97.711 MPa) (Table 4).

The stress values were higher in the cantilevered groups than in the noncantilevered groups. The presence of a cantilever increased the stress on the framework, regardless of the material used. Furthermore, the stress levels increased for all the framework materials (Fig. 4). The highest stress values in the abutments were detected in the cantilevered models located in the posterior region and with a PEEK framework (553.259 MPa and 472.881 MPa). In contrast, these values were significantly lower in the Co-Cr and zirconium framework models (Table 4).

Fig. 4. Von Mises stress distribution (MPa) in the titanium and zirconia implant bodies under oblique loading conditions.

When the ceramic and titanium implants were compared, the maximum principal stress values in the cortical bone were quite close to each other (Fig. 5). The highest compressive stresses in the cortical and trabecular bone tissues were detected in the posterior implant regions (Fig. 6).

Fig. 5. Maximum principal stress values (MPa) and stress distribution in maxillary cortical bone under oblique loading

Fig. 6. Maximum principal stress distribution (MPa) in the maxillary trabecular bone under oblique loading conditions.

The amount of displacement in the cantilevered prostheses was greater than that in the noncantilevered groups (Fig. 7). While the values obtained for titanium and zirconia implants were similar, the amount of prosthetic displacement in the PEKK framework models was found to be greater than that in the models using Co-Cr and zirconium frameworks. (Table 4).

Fig. 7. Displacement values

Table 4. Von Mises and principal stress extreme values for each component are presented separately, and all values are expressed in megapascals (MPa).

4.DISCUSSION

Zirconia implants have a higher elastic modulus than titanium implants. According to Hooke's law, as the elastic modulus of a material increases, its resistance to deformation increases, and a higher level of stress occurs under constant deformation conditions. This mechanical property causes zirconia implants to absorb applied loads to a greater extent than titanium implants. Indeed, Pérez-Pevida et al. demonstrated that stiffer implants structurally accommodate more stress under the same loading and design conditions [21]. Similarly, a finite element analysis conducted by Bal et al. reported that zirconia implants exhibited higher stress values than titanium implants [22]. This study found that zirconia implants created higher stress accumulation than titanium implants in all regions, which is consistent with previous findings in the literature. When groups without cantilevers were compared, the higher von Mises stress levels in the zirconia implants than in the titanium implants can be attributed to the high elastic modulus of the zirconium material, resulting in stress being absorbed within its own structure.

In implant-supported fixed prostheses, the framework material plays a decisive role in the transmission of occlusal forces to the implant and peri-implant bone tissues [23]. PEKK, a type of high-performance polymer, is increasingly preferred in clinical applications due to its biocompatibility, aesthetic advantages, low density, and ease of processing. Compared with

PEEK, PEKK offers greater compressive strength and improved mechanical properties, making it an aesthetically strong alternative to traditional cobalt-chromium frameworks in fixed prostheses [17,18,24]. On the other hand, its low elastic modulus is considered a limiting factor in terms of long-term biomechanical stability, as it transmits more stress to peri-implant tissues and leads to high prosthetic displacement. Findings in the literature regarding PEKK's load transfer dynamics show conflicting results. While some studies report that its flexible structure reduces stress levels in the implant and surrounding bone, others have shown that it increases stress accumulation, particularly in the implant neck region where tensile stresses are concentrated [18,25]. Consistent with the literature, this study found that compared with those in the Co-Cr and zirconium framework models, the von Mises stress levels in all the groups in the PEKK framework models were greater. Therefore, the indications for PEKK frameworks should be carefully evaluated, especially in cases involving bruxism or parafunctional habits.

It has been reported that stress accumulation in distal implants and the associated risk of marginal bone loss increase in the presence of cantilevers; therefore, cantilever-free prosthesis designs are recommended to improve stress distribution. Silva et al. reported that maximum von Mises stress values increased by approximately 100% in the presence of cantilevers [26]. Horita et al. [27] demonstrated that peak stress decreased by 45.3–52.5% in cantilever-free applications, emphasizing the biomechanical importance of cantilever elimination. Similarly, Keshavarz Valian et al. reported that reducing the cantilever length significantly decreased stress accumulation [28]. These results are consistent with the stress increase observed in the presence of a cantilever in our current study and indicate that the cantilever length should be carefully planned from a clinical perspective. Similarly, this study also showed that stress values were higher in the cantilevered designs than in noncantilevered designs. Therefore, when low elastic modulus framework materials such as PEKK are used, cantilever-free designs should be preferred to balance the stress distribution and prevent excessive stress on the implant–screw. In cases where the use of a distal cantilever is unavoidable, the selection of high-rigidity framework materials such as Co-Cr or zirconium may contribute to reducing the stress transmitted to the peri-implant tissues and preserving long-term biomechanical stability and functional integrity.

In the literature, it has been reported that zirconia implants create lower stress peaks than titanium implants do, particularly in the cortical bone surrounding the implant platform [29]. In the present study, zirconia implants also transmitted slightly lower stress to the bone than titanium implants. The forces transmitted to cortical and cancellous bone are clinically significant in terms of preventing stress shielding. According to Harold M. Frost's theory, bone tissue responds physiologically to mechanical stresses in the range of 2–40 MPa (100–2000 με); within these limits, bone mass is preserved or increased [30]. On the other hand, a study by Baggi and colleagues indicated that loads exceeding 5 MPa in trabecular bone are associated with overload and may increase the resorptive response [31]. Therefore, in implant-supported restorations, transmitting stress to the bone within physiological limits, preventing the stress shielding effect, and preserving peri-implant bone integrity are important factors to consider.

Stress levels exceeding physiological limits were detected in trabecular bone in the cantilevered PEKK framework model (Group 3: 8.723 MPa; Group 6: 8.583 MPa). Similarly, Sirandoni et al. [15] compared different frame materials in full-arch prostheses and reported that Co-Cr and zirconium, which have high elasticity moduli, remained within physiological limits in bone, whereas flexible materials caused tensile stresses exceeding critical limits in trabecular bone. The results of the study by Şahin et al. using PEEK material are similar to our current findings [32]. It is thought that the force of the PEKK material is largely transmitted to the implant and then to the bone, thereby further increasing the stress levels in trabecular bone. However, angulated distal implant placements, which are recommended to reduce this effect, have also been reported to possibly cause local stress increases in the implant neck and marginal bone [33]. Similar to previous FEA studies, this study also confirms that the highest stresses are mostly concentrated in the neck region of most distal implants [33–35]. This is related to the moment arm effect at the point where the restoration ends in the posterior region and the bending moments are created by occlusal forces . Studies have reported that loading direction also plays a decisive role in this mechanism; specifically, oblique forces create a bending moment in the buccolingual direction, leading to higher von Mises stresses in distal implants than in vertical loading [36]. The results support that cantilever use and oblique loading lead to stress concentration in distal implants; therefore, it is necessary to optimize the implant placement angle, implant number, and prosthesis design, especially in posterior regions, to ensure a balanced distribution of occlusal forces.

Prosthesis displacement is a critical indicator of biomechanical success in full-arch implant-supported restorations. Current findings indicate that low-elasticity modulus PEEK frameworks exhibit greater displacement under occlusal loads than zirconium and Co-Cr frameworks [32,37]. This situation can lead to reduced chewing efficiency and compromised occlusal stability, especially in the presence of cantilevers. It has been reported that increasing the number of implants resulted in a 16% improvement in displacement levels [38]. It is anticipated that the amount of prosthetic displacement can be optimized by the number and location of implants, the selection of high-rigidity framework materials, and a cantilever-free prosthesis design.

Compared with vertical implants, angular implants tend to generate greater bending moments because they are more exposed to the lateral components of occlusal forces. One study reported that the Von Mises values measured at the neck of angled implants were greater than those measured at the neck of vertical implants, and greater stress accumulation was also observed around the peri-implant bone [39]. In contrast, lower stress values were recorded in both the implant components and the surrounding bone in the vertical implants. Similarly, in our study, inclined implants were found to generate higher stress values both at the implant level and in the peri-implant bone , which is consistent with findings reported in the literature.

The literature indicates that the fracture threshold of zirconia implants under static forces varies depending on the implant design, diameter, loading conditions, manufacturing method, and material composition, with values ranging from 372.4–783 N [40–43]. A study by Ward et al. reported that the typical flexural strength of 3Y-TZP ceramic is in the range of 950–1310 MPa [44]. Another finite element analysis indicated that the average flexural strength of 3Y-TZP is 952 MPa and that zirconia implants could be safely used under chewing loads up to 500 N [45]. In this study, the tensile stress values obtained in all the groups remained within the safe loading limits reported in the literature; the stress values measured in zirconia implants ranged from 59.075 to 378.388 MPa, and therefore, the safety margin was maintained. The risk of fracture in zirconia implants is low under the applied scenarios. These findings show that zirconia implants are a good alternative not only because of their aesthetic superiority but also because of their safe performance under suitable mechanical conditions.

Although finite element analysis is effective for evaluating stress distribution and material behavior, it cannot fully reflect intraoral biomechanical and biological conditions, thus limiting the direct generalization of clinical results. Furthermore, mucosal tissue was not included in the modeling process, assuming its minimal effect on the distribution of peri-implant stress. The analyses were performed with a loading condition applied in a single region from an oblique direction; however, in the clinical environment, the direction and intensity of occlusal forces vary with each cycle, which can directly affect fatigue resistance and long-term performance.

Due to differences in the surface properties of zirconia and titanium, changes in bone integration, healing time, and associated force transmission may occur; furthermore, the fact that microcracks possibly occurring during surface treatments can increase the risk of fracture has been neglected [46,47]. Dynamic analysis was not performed because the primary objective of this study was to compare the stress distribution among different implants, framework materials, and prosthesis designs. Therefore, linear static analysis was preferred. In addition, the titanium and zirconia implant systems used in this study were not fully identical in terms of connection design, implant geometry, and thread characteristics. Accordingly, the observed biomechanical differences should be interpreted as the combined effect of material properties and system-specific design features. However, supporting the findings with long-term clinical follow-up and dynamic load tests is important for demonstrating the biomechanical reliability of zirconia implants in a more robust and comprehensive manner. Taken together, these considerations outline the principal limitations of the present study.

5.Conclusion

The results of this study demonstrate that zirconia implants, despite exhibiting higher stress concentrations within the implant body compared with titanium implants, remain within physiologically safe limits and can be used with mechanical confidence under appropriate clinical conditions. The presence of cantilevers increased the stress in all the models, whereas the stress and displacement values of the PEKK frameworks were higher than those of other models. In contrast, implants positioned vertically with Co-Cr and zirconium framework provided more balanced biomechanical results. Clinically, it is recommended that the number and location of zirconia implants be planned carefully to reduce the risk of complications, that rigid framework materials be preferred, and that cantilever-free designs be used whenever possible. However, since finite element analysis cannot fully reflect biological and functional conditions, it is crucial to support these findings with long-term clinical follow-up and dynamic load tests.

6. Declarations

Abbreviations

FEA Finite Element Analysis

Zr Zirconium

Co-Cr Cobalt chromium

PEKK Polyetherketonketone

Y-TZP yttria-stabilised tetragonal zirconia polycrystals

CT computed tomography

STL stereolithography

SEM Scanning electron microscopy

EDX Energy-dispersive X-ray spectroscopy

XRD X-ray diffraction

Ethical approval and consent to participate

Not applicable

Publication approval

Not applicable

Ethics, Consent to Participate, and Consent to Publish declarations

not applicable.

Availability of data and materials

Data are presented within the article.

Conflict of interest

The authors declare no conflict of interest.

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Authors' contributions

B.S. wrote the article and performed the analyses. O.D.O. and O.Y.O. reviewed and revised the article. All authors reviewed the article and contributed to the development of the concept.

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