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Original research article

The stress distribution of implants made of Polyaryletherketones: A 3D Finite Element Analysis

Ahmet Serkan Küçükekenci,[1*]
Mehmet Sami Güler,[2] **Muhammed Latif Bekci**[3]

[1]Department of Prosthodontics, Faculty of Dentistry, Ordu University, Ordu, Turkey [2]Department of Machinery Metal Technologies, Vocational School of Technical Sciences, Ordu University, Ordu, Turkey, [3]Department of Motor Vehicles and Transportation Technologies, Vocational School of Technical Sciences, Ordu University, Ordu, Turkey.

Abstract

Objective: To explore the stress distribution on the bone-implant structures caused by the Polyetheretherketone (PEEK), Polyetherketoneketone (PEKK), and titanium fixture/abutments by using the three-dimensional (3D) finite element analysis (FEA).

Materials and Methods: Six models composed of titanium, PEEK, and PEKK implant/abutments under vertical (250 N) and 45˚ oblique (100 N) loading were studied. The obtained principal and von Mises stress values from the models were evaluated.

Results: von Mises stresses were found to be highest in titanium implants and abutments under vertical and oblique loads. Extremely increased stress values were observed in the screws of the Polyaryletherketone (PAEK) models compared to titanium models. Lower principal stresses were observed in titanium models than in PAEK models in the cancellous and cortical bone under vertical and oblique loads.

Conclusion: PAEKs transmitted more stress to the peri-implant bone. Stress distribution in titanium models was more homogenous while stress concentrated in the bone adjacent to the coronal part of the implants and neck of the implants in PAEKs.

Keywords: Dental implants; dental stress analysis; elastic modulus, polymers.

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*Corresponding author: Ahmet Serkan Küçükekenci, Ordu University, Faculty of Dentistry, Ordu, Turkey
E-mail: serkankucukekenci@gmail.com

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[Abstract in Turkish is at the end of the manuscript]

Introduction

With the developments in the biomedical era rehabilitation of tooth loss with implant-supported restorations (ISR) has become a predictable treatment option with high clinical success and patient satisfaction.[1-3] The long-term success of ISR is closely associated with the manner of stress dissipation at the bone-implant interface since, due to a lack of periodontal ligament, the occlusal loads are directly transferred by the implant to the bone.[4] Besides, a certain amount of stress is required to maintain a healthy bone-implant interface; if the loads transferred to the bone remain below the level to induce remodelling or exceed its carrying capacity, it may lead to failure of the implant. Thus, the provision of adequate stress dissipation is crucial for the long term survival of ISRs.[5,6]

Stress dissipation in ISR is strictly associated with the characteristics and mechanical behaviours of the implant and the restorative materials.[5] Currently, titanium is still the gold standard and the most widely preferred material in dental implantology due to its biocompatibility and osseointegration capacity.[3] However, the elasticity modulus of titanium which is higher than that of the bone poses a challenge. This mismatch between the elasticity modulus of titanium and bone is considered to generate high stress at the bone-implant interface in function and lead to resorption in the peri-implant bone because of stress shielding.[7,8] Also, titanium has drawbacks like plaque accumulation affinity, leading to corrosion, scattering during radiographic imaging, causing allergic or local tissue reactions, and having non-aesthetical color.[7,9] To overcome the shortcomings of titanium, zirconia-ceramic was proposed for dental implant applications as a metal-free alternative. Zirconia has favourable biocompatibility along with lower plaque accumulation and has enough strength against masticatory loads. Although the osseointegration capacity and survival of zirconia are similar to titanium, disadvantages of zirconia are high elasticity modulus, brittleness aging, and implant-degradation.[3,8,10]

Polyaryletherketones (PAEKs) have become an area of interest in the field of implantology as a response to the growing need for new materials that have mechanical characteristics similar to that of bone. PAEKs are thermoplastic polymers, that have been increasingly used in orthopedics, traumatology, spinal, neurosurgical, cardiovascular, and craniofacial surgical procedures due to their biocompatibility, excellent mechanical strength, and radiolucency since the 1990s.[8,11,12] One of the representatives of this family, Polyetheretherketone (PEEK) is a high-performance thermoplastic polymer that has taken the place of metallic implant components in the fields of traumatology and orthopedics since 1998.[13] PEEK has been popular in dentistry with its several advantages, including having an elastic modulus (3.6 GPa) closer to that of bone that can be modified by reinforcing it with carbon fibers to achieve a modulus of 18 GPa similar to that of cortical bone, esthetic appearance, having low plaque affinity, physical and chemical stability, and corrosion resistance.[7,12,14] PEEK has been used in dental applications more commonly as an alternative material in healing abutments and prosthetic dental components.[9,15] Polyetherketoneketone (PEKK Cendres + Métaux SA, Biel / Bienne, Switzerland) is another member of the PAEK family which was introduced more recently as an improved material having more ketone groups than PEEK. It was reported revealing higher strength and thermal stability, better fatigue, the versatility of surface modification, and higher structural variation than PEEK.[11,16,17] In the dental field PEKK has been used in the manufacturing of frameworks.[15,17]

Mechanical and physical characteristics of implant material have an important role in stress distribution. It is considered that materials with stiffness closer to the bone might lead to better stress distribution and also, may reduce the stress shielding effect.[5,8] Thus, PEEK and PEKK seem to be valid alternatives to titanium in dental implant applications. Good osteointegration properties are essential for the long-term stability of an orthopedic/dental implant planned to be used.[18] However, it has been reported in some previous studies that fibrous encapsulation may form at the interface between PAEK implants and bone, which may lead to clinical instability under load-bearing conditions.[19,20] Some *in vitro* and *in vivo* animal studies have been reported in which the osteointegration property of PEEK was improved by using methods such as composites containing bioactive fillers (hydroxyapatite, beta-tricalcium phosphate, and bioactive glasses), surface modification by physical or chemical methods (plasma-sprayed titanium coating, oxygen plasma and sandblasting), and scaffolds consisting of three-dimensional porous structures.[11,21-24]

Finite element analysis (FEA) has been used in dentistry to simulate different anatomical structures and clinical conditions through a mathematical model without the risk and expense for many years. It can widely be used to evaluate the effects of masticatory forces on dental implants and jaw bones. Different stress analyses are conducted for ductile and brittle materials. The von Mises stress analysis is used for ductile materials, while the maximum and minimum principal stress analyses are used for brittle materials. The von Mises stress is commonly used as a stress metric. Maximum principal stress defines the maximum tensile stress, and minimum principal stress defines the maximum compressive stress.[4,25]

To the best of our knowledge, there is no study evaluating the biomechanically PEKK as an implant material. Also, in the literature evidence is scarce in terms of the usage of the PEEK as an alternative material in dental implantology. Therefore, this study aims to explore the stress distribution on the adjacent bone tissue and implant structures caused by the PEEK, PEKK, and titanium fixture/abutments by using the three-dimensional (3D) finite element analysis (FEA). The null hypothesis of the present study was that the implant material being PEEK, PEKK or titanium would not affect the stress distribution on the adjacent bone tissue and implant structures.

Materials and Methods

FEA models

In this study six models were constructed:

Model 1A: Titanium implant with titanium abutment and connecting screw, and vertical load

Model 1B: Titanium implant with titanium abutment and connecting screw, and 45˚ oblique load

Model 2A: PEEK implant with PEEK abutment and titanium connecting screw, and vertical load

Model 2B: PEEK implant with PEEK abutment and titanium connecting screw, and 45˚ oblique load

Model 3A: PEKK implant with PEKK abutment and titanium connecting screw, and vertical load

Model 3B: PEKK implant with PEKK abutment and titanium connecting screw, and 45˚ oblique load

Vita Enamic (VITA Zahnfabrik Bad Sackingen, Germany) was used as a crown material in all models.

Solid models

A maxillary bone model obtained by cone-beam tomography (KaVo OP 3D Vision, Imaging Sciences International LLC, USA) was used in this study. Modeling of the maxillary bone with a 1 mm cortical

Figure 1. 3D modeling of maxillary cortical and trabecular bones, implant, abutment, screw, and crown.

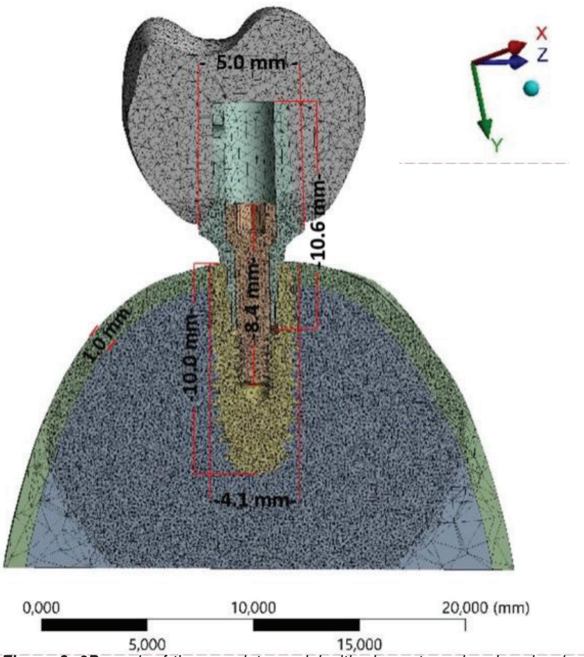

Figure 2. 3D mesh of the complete model with elements and nodes showing the dimensions of the implant, abutment, screw, and cortical bone.

and backward trabecular bone was performed in 3D modelling software (SolidWorks 15, SolidWorks Corporation, Waltham, MA, USA). The 3D models of a 4.1-10 mm bone-level implant (T6 4110), a standard straight abutment (T6 SD045), and a connection screw (T6 16000) were supplied from the NucleOSS (Nucleoss, Izmir, Türkiye). For the modeling of the crown the sizes and images of the upper first molar tooth were taken from Wheeler's Dental Anatomy Atlas.[26] With the same software, for the simulation of *in vivo* conditions the ISRs were placed in the right first molar region of the maxilla (Fig. 1).

FEA

The model was exported to ANSYS 13 Workbench software (Swanson ANSYS Inc, Houston, PA, USA). Three-dimensional meshes were obtained by using ten-node tetrahedral elements for all solid models (Fig. 2). The FE model consists of 4994287 nodes and 3646665 elements. To simulate 100% osseointegration the implants were simulated as rigidly attached to the bone. FE analyses were conducted on a desktop with Intel Core i7-4790 eight-core processor and 16 GB RAM. Each analysis took approximately 45 minutes of CPU time.

Properties of the materials

In the present study, all models were treated to be homogeneous, isotropic, and linear elastic and considered to be in continuous contact with each other. An identical and 100 % bone-implant contact was assumed for all models studied. The implant-bone interface is assumed identical for all models. The properties of materials were obtained from the previous studies and the manufacturers (Table 1). Models are restricted without movement in the x, y, and z axes.

Loading conditions

The applied forces were static. At vertical load condition, 250 N force applied to five surfaces. At oblique load condition (45˚), 100 N force was applied to two surfaces (50 N per surface) (Fig. 3).[27,28]

***Table 1.** Material properties used in the FEA*

Geometry	Young Modulus [GPa]	Poisson Ratio
Cortical bone	13.7[40]	0.3[40]
Cancellous bone	1.37[40]	0.3[40]
Crown (Vita Enamic)	30[4]	0.23[41]
Abutment and Implant (PEEK)	5.1[*]	0.36[2*]
Abutment and Implant (PEKK)	5.1[*]	0.4[*]
Abutment and Implant (Titanium)	110[40]	0.35[40]
Screw (Titanium)	110[40]	0.35[40]

**: Values obtained from manufacturer*

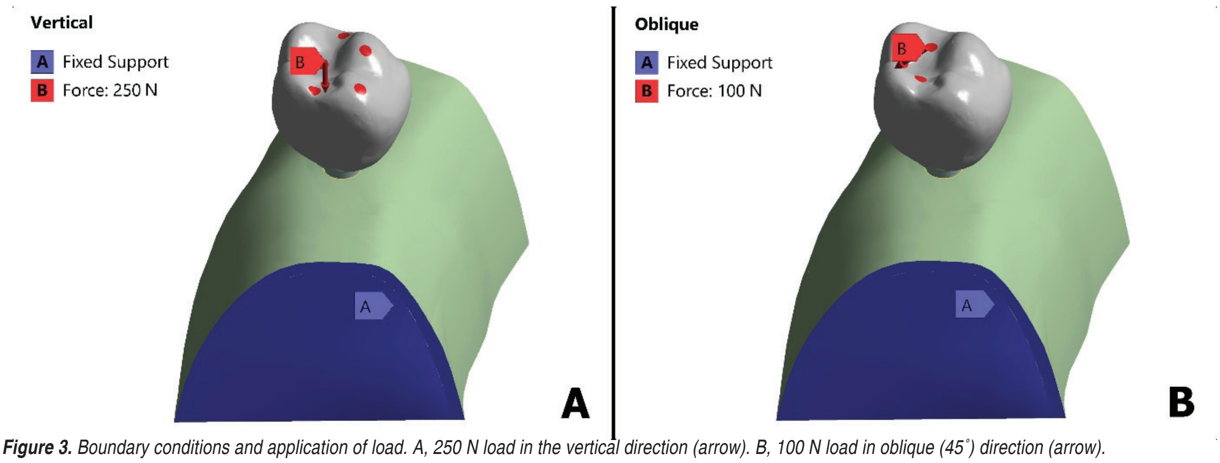

Figure 3. *Boundary conditions and application of load. A, 250 N load in the vertical direction (arrow). B, 100 N load in oblique (45°) direction (arrow).*

Results

Von Mises stress in implants, abutments, and screws

Von Mises stresses were found to be highest in titanium implant (135.69 MPa; 400.1 MPa) while lower and similar stress values were observed in PEEK (86.90 MPa; 270.48 MPa) and PEKK (87.38 MPa; 268.15 MPa) implants under vertical and oblique loads, respectively. Although stress was more homogeneously distributed in titanium implants under both vertical and oblique forces, the highest stress value was observed in the neck region of the implant model compared to PAEKs (Fig. 4, Table 2).

Regarding abutments, stress concentration was observed in the implant-abutment connection area of the abutments in all models. Abutments in the titanium implant models (172.96 MPa; 523.46 MPa) showed the highest von Mises stress compared to the PAEK models (PEEK:99.71 MPa; 256.55 MPa/ PEKK:95.96 MPa; 252.45 MPa) under vertical and oblique loads (Fig. 4, Table 2).

In terms of the titanium screws in all models, the highest von Mises stress was observed in the PEEK model under vertical and oblique loads (411.13 MPa; 1290 MPa). Similar values were also found in the PEKK model under vertical and oblique loads (402.12 MPa; 1259.5 MPa). Screws in the titanium model exhibit the lowest von Mises stress values (73.65 MPa; 165.6 MPa) under vertical and oblique loads, respectively. A dramatically increased stress value was observed under the oblique loading in the screws of the PAEK models compared to titanium (Fig. 4, Table 2).

Principal stress in the bone

Cortical bone

Similar maximum principal stress values were observed in all models under vertical loading in titanium (42.97 MPa), PEEK (42.66 MPa), and PEKK (43.17 MPa) models. Similar minimum principal stress values under vertical loads were observed in PEEK (-52.68 MPa) and PEKK (-52.38 MPa) models. Also, the lowest minimum principal stress value under vertical loads was observed in the titanium model (-30.28 MPa). In all models, stress is concentrated in the cortical bone adjacent to the implant neck under vertical load (Fig. 5, Table 2).

In oblique loading, titanium models showed lower maximum (54.18 MPa) and minimum (48.45 MPa) principal stresses compared to the PEKK (144.14 MPa; -176.36 MPa) and PEEK (141.6 MPa; -177.57 MPa) models. Stress concentration was observed more dominantly in the cortical bone around the implant neck in PEEK and PEKK models. In the titanium model more homogenous stress distribution was observed in cortical bone (Fig. 5, Table 2).

Cancellous bone

In cancellous bone, lower stress values compared to the cortical bone were observed in all models. Similar principal stress values under vertical load were observed in PEEK (21.93MPa; -5.92 MPa) and PEKK (22.45 MPa; -5.94 MPa) models. Lower maximum and similar minimum principal stress values under vertical load were observed in the titanium model under vertical load (10.66MPa; -6.53 MPa). Higher minimum principal stress concentration was observed in the apical region of the implant in the titanium model while seen around the neck of the implant in PAEK models. The maximum principal stress distribution was observed more homogenous in the titanium model for cancellous bone compared to PAEK models (Fig. 6, Table 2).

Under oblique loading, PEEK (23.69MPa; -16.45 MPa) and PEKK (24.90 MPa; -17.26 MPa) models showed similar principal stress values. The titanium model exhibited the lowest principal stress values (9.57MPa; -5.70 MPa). More homogenous stress distribution was observed in the titanium model while in PEEK and PEKK models maximum and minimum principal stress concentrated in the bone adjacent to the neck region of the implants (Fig. 6, Table 2).

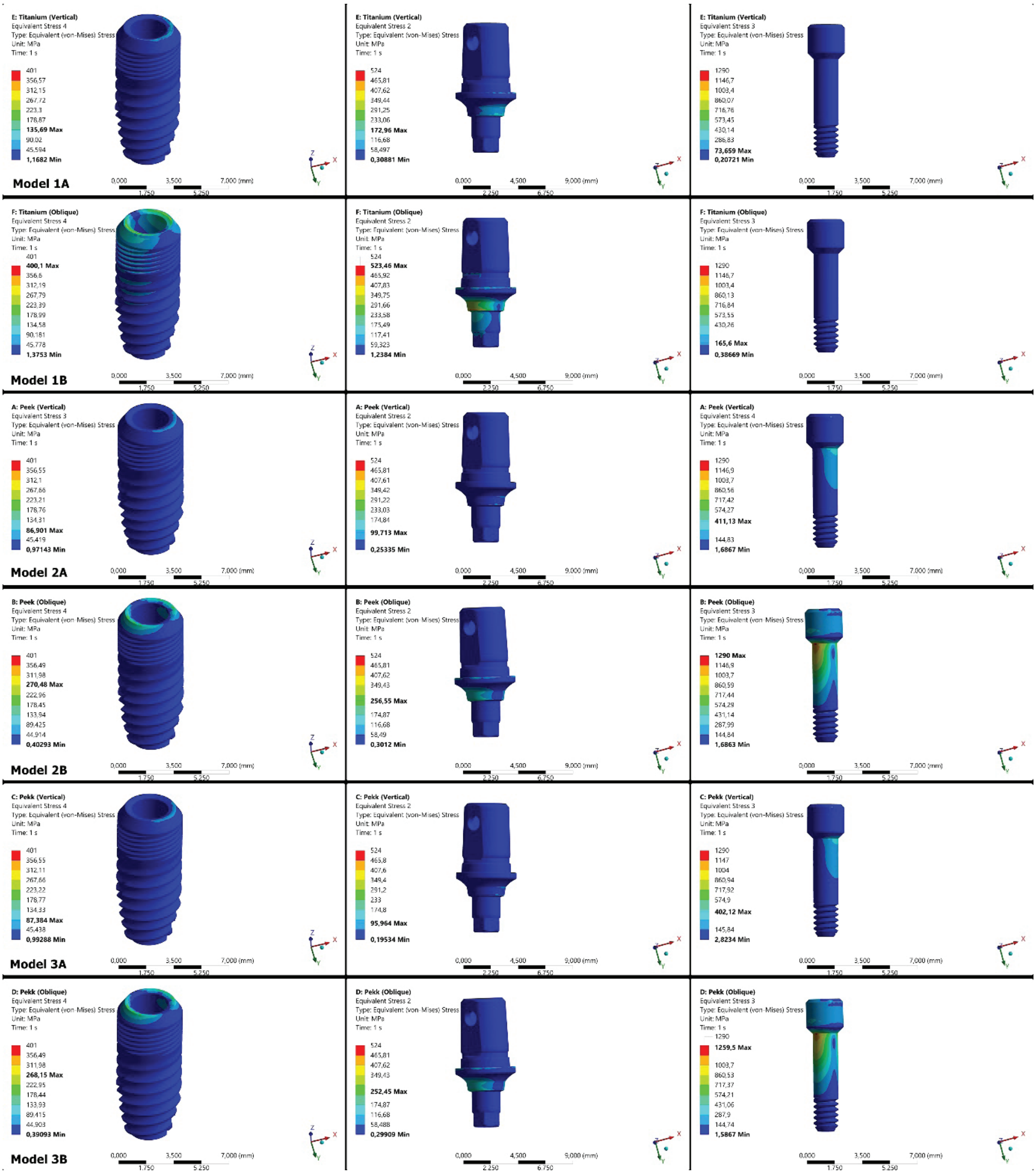

Figure 4. von Mises stress values in study models.

Table 2. FEA results in terms of critical stress values

Geometry	Stress [MPa]	Titanium		PEEK		PEKK	
		Model 1A	**Model 1B**	**Model 2A**	**Model 2B**	**Model 3A**	**Model 3B**
		Vertical	Oblique	Vertical	Oblique	Vertical	Oblique
Cortical bone	Max. Principal	42.975	54.189	42.664	141.6	43.178	144.14
	Min. Principal	-30.284	-48.455	-52.682	-177.57	-52.385	-176.36
Cancellous bone	Max. Principal	10.665	9.5798	21.933	23.696	22.455	24.909
	Min. Principal	-6.5392	-5.7039	-5.9292	-16.452	-5.9449	-17.262
Abutment	Max. von Mises	172.96	523.46	99.713	256.55	95.964	252.45
Screw	Max. von Mises	73.659	165.6	411.13	1290	402.12	1259.5
Implant	Max. von Mises	135.69	400.1	86.901	270.48	87.384	268.15

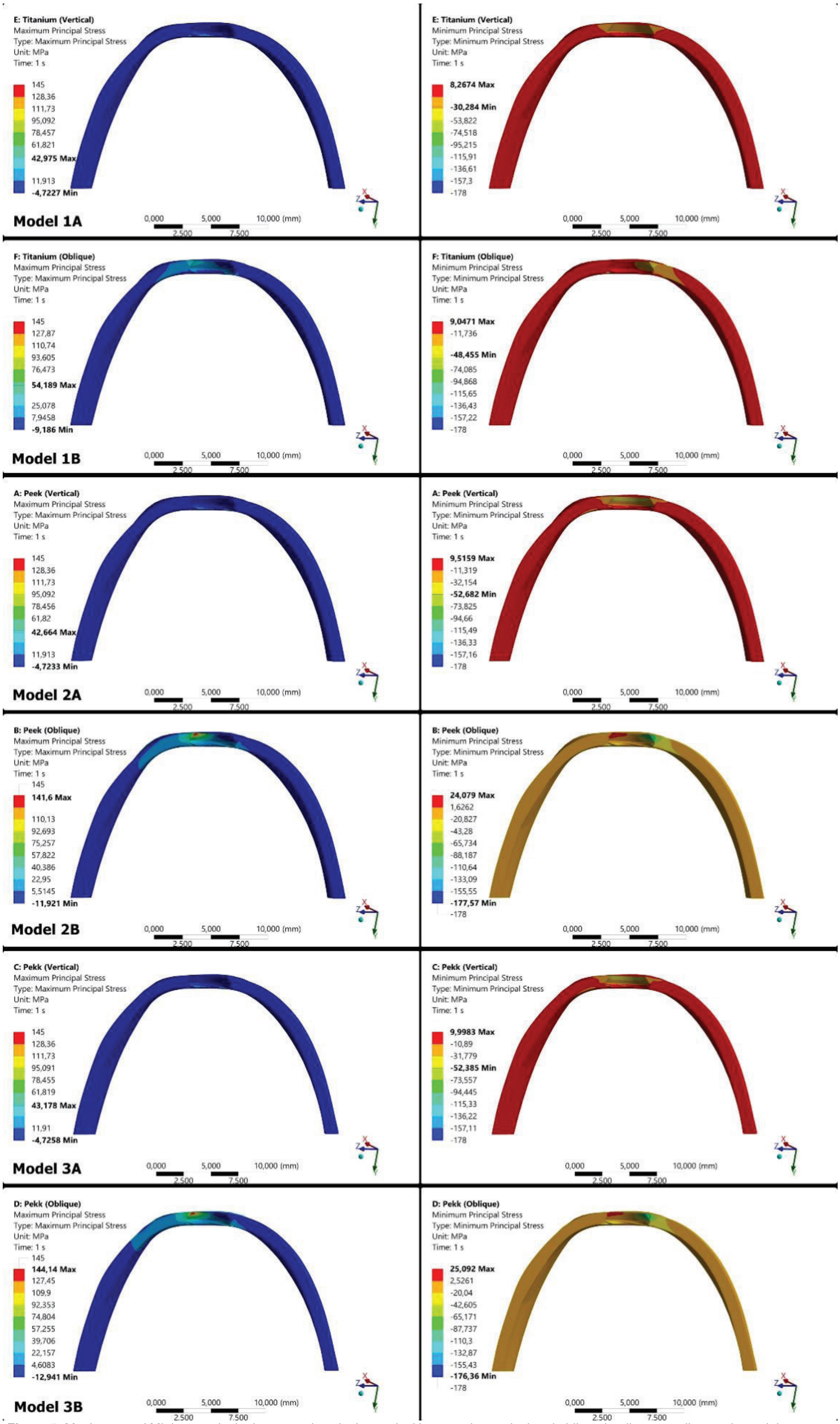

Figure 5. *Maximum and Minimum principal stress values in the cortical bone under vertical and oblique loading regarding study models.*

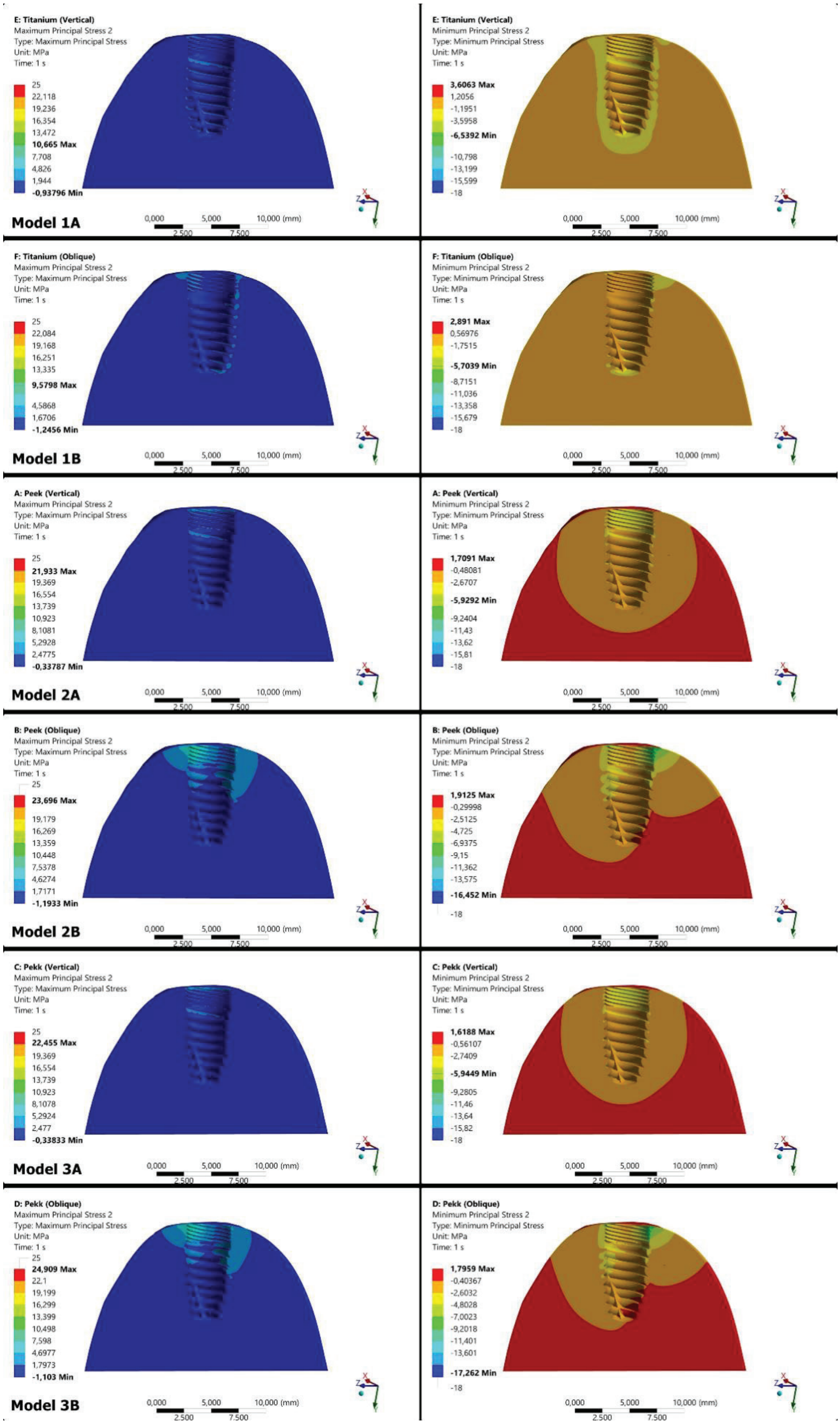

Figure 6. *Maximum and Minimum principal stress values in cancellous bone under vertical and oblique loading regarding study models.*

Discussion

The usage of PAEK polymers with an elasticity modulus closer to the bone is nowadays popular in implantology with an expectation of creating better stress distribution and prevention of stress shielding effect caused by stiffer materials like titanium. The promising reports in orthopedics, spinal applications, and traumatology[13,29,30,] give rise to the idea of using these materials in dental implantology, and the current paradigm favors the materials with lower Young's modulus.[6] However, the evidence is still not enough for a generalized conclusion since the occurrence of stress shielding in dental implantology and the applicability of this concept in jawbones lack a clear reference.[6,31] Limited number of studies explored stress distribution caused by these materials in dental implantology.[3,5,6,12,32]

This study aimed to determine the effect of replacing titanium with PAEKs as an implant/abutment material on stress distribution. To accomplish this goal, we used FEA, which is an effective way to explore mechanical behavior and the feasibility of the materials. By creating simpler geometries from a complex geometry with known boundary conditions, stress distribution on dental implants, surrounding bone, and restorative elements during function can be predicted by FEA.[4,5] Due to the complex structure of ISR and, the complicated relation between the components, a great number of elements are needed to simulate the load transfer accurately.[5] A model with 3 646 665 elements was used for the simulations in this study. Bite forces are widely variable among people.[12,33] Thus, representing real clinical condition *in vitro* is certainly difficult.[32] Different bite forces with different angulations applied in previous studies.[5,12,25,32,34,35] To simulate the real function we applied 250 N vertical and 100N (45°) oblique static loads on the maxillary first molar tooth's occlusal surface.[27,28]

According to results of the present study, the null hypothesis was rejected. Both vertical and oblique loading higher von Mises stress was observed on implant and abutment in the titanium models. Lower and similar stress values were observed in PEEK and PEKK models. In all models, abutments exhibit more stress values when compared to the implants except abutments of PEEK and PEEK models in oblique loading. Bataineh and Al Janaideh[5] found higher von Mises values in the titanium fixture/abutment model than the Carbon-fiber-reinforced polyetheretherketone (CFR-PEEK) model within both models' abutments show higher stress values than implants under oblique loading. Sarot *et al.*[32] however, found higher von Mises values in CFR-PEEK fixture and lower values seen in CFR-PEEK abutment compared to the titanium fixture/abutment model under vertical and oblique loads. They observed a more homogeneously distributed stress in the titanium model. In the study of Schiwalla *et al.*[12] while similar von Mises stresses were observed in Titanium and CFR-PEEK fixture/abutment models, PEEK caused higher von Mises stress against 100N (vertical and oblique) loading. The authors think that a possible explanation of this result is the underestimation of the viscous damping effect of the PEEK which results in stress relaxation, because of the simplification of the FEA by assuming the materials to be linearly elastic and isotropic.

Although better stress distribution is expected in models with lower elasticity modulus, in some previous studies, it is reported that the occlusal loads lead tendency to higher stress in the implant neck of both titanium, PEEK, and CFR-PEEK models.[5,12] Similar to these studies, in the present study, higher stress concentration in the implant neck was both observed in titanium, PEEK, and PEKK models. Sarot *et al.*[32] found higher load concentration limited area of the neck in the CFR-PEEK model, while a more homogenous distribution was observed by the authors in titanium models. The authors attributed this result to the fact that despite the orthopedic applications, implant and bone have a rigid bond that leads to inherent deformation in CFR-PEEK, which causes a concentration of more stress in the implant neck. In this study, although more homogeneous stress distribution was observed in titanium implants under both vertical and oblique forces, the stress value in the neck region of the implant was higher compared to PAEKs.

Regarding the prosthetic screw, Tretto *et al.*[3] reported that the ideal adaptation of the abutment and implant leads to lower stress in the screw making the material of the abutment is not relevant. However, in this study, higher stress values were also found in screws of PEEK and PEKK models, which concentrated at the neck region compared to the titanium model. This difference in the results may be caused by the difference between the designs and the implant-abutment connection type between the studies. Also, maybe originated from that in PEEK and PEKK models the stiffer material is the prosthetic screw and it absorbs most of the stress generated.

Because of the increased deformation tendency of the materials to have a lower modulus of elasticity under loads higher stress was transmitted to the adjacent peri-implant bone.[3] In the study of Lee *et al.*[8] higher stress values were found in the peri-implant bone adjacent to the material with lower elasticity (PEEK) while lower stress was observed in stiffer materials (zirconia and titanium) against vertical and horizontal loading. According to these researchers' PEEK implants or PEEK coating may reduce the stress shielding effect. Korabi *et al.*[6] in their study conducted with the failure envelope concept claimed the opposite and refused the paradigm favoring materials with lower elasticity modulus. In some studies, stress distribution in peri-implant bone was found similar in titanium and CFR-PEEK while lower than in pure PEEK.[5,12] Regarding stress in peri-implant bone in this study similar values were observed in all models for cortical bone in vertical loading. However, in oblique loading PEEK and PEKK exhibit, higher stress values concentrated in the upper bone-implant interface of cortical bone compared to the titanium. Cancellous bone exhibits lower stress than cortical bone in all models. Observed stress values in peri-implant bone may differ among the studies regarding the assumption that the bone isotropic or anisotropic. As an anisotropic material, the physical properties of bone are affected by the direction.[36] In the present study, the bone was assumed to be isotropic, linear elastic, homogeneous, and also 100 % osseointegration assumed. These do not demonstrate real clinical conditions. However, it is reported that the results of 100 % osseointegration and nonlinear contacts between bone-implants are similar.[37]

The transfer of the forces to the implants and the surrounding bone is direction dependent. A non-axial load that generates bending moment and leads to higher stress is more harmful while axial loads are well-tolerated.[5] In terms of the off axis loading in concordance with the literature higher stress values in bone and implant structures were observed in all models of this study.

In this study, the vertical loads applied at and near the center of the tooth were divided between the buccal and palatal cusps, and the oblique loads were applied directly to the buccal ridge, so the vertical and oblique load intensities were not equal. Increased stress levels in peripheral bone and prosthetic components have also been reported with oblique loading. For long-term survival, occlusal interference must be eliminated, and optimal occlusal harmony for centric and eccentric movements must be ensured.[4,38,39]

This study has some limitations that should be considered when interpreting the results. Since this is an FEA study it only provides a mechanical review and could not demonstrate real clinical conditions and forces during chewing, since the patient may have different bite forces and frequency of chewing when the implant is under use. On other hand, the material properties were assumed to be homogeneous, isotropic, and linearly elastic, but that may not necessarily reflect the practical case.

Conclusion

PAEKs transmit higher forces to the peri-implant bone while exhibiting lower stress in implant and abutment compared to titanium, especially in oblique loading. Stress distribution in titanium models was more homogenous, however, stress concentration in the bone adjacent to the coronal part of the implant and neck of the implants were observed in PAEKs. In all conditions, PAEK models showed similar behavior against loads. It is required to determine the occurrence of stress shielding in dental implantology and the applicability of this concept in jawbones to determine the advantages and real feasibility of PAEKs in dental implantology.

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Poliarileterketonlardan yapılmış implantların stres dağılımı: 3 boyutlu Sonlu Elemanlar Analizi

ÖZET

AMAÇ: Bu çalışmanın amacı, üç boyutlu (3D) sonlu elemanlar analizi (SEA) kullanarak Polietereterketon (PEEK), Polieterketonketon (PEKK) ve titanyum implant/dayanakların kemik-implant yapılarında neden olduğu stres dağılımını araştırmak.

GEREÇ VE YÖNTEM: Dikey (250 N) ve 45˚ oblik (100 N) yükleme altında titanyum, PEEK ve PEKK implant/dayanaklardan oluşan 6 model üzerinde çalışıldı. Modellerden elde edilen principal ve von Mises stres değerleri değerlendirildi.

BULGULAR: von Mises gerilme değerlerinin dikey ve oblik yükler altında titanyum implantlarda ve dayanaklarda en yüksek olduğu bulundu. Poliarileterketon (PAEK) modellerin vidalarında titanyum modellere göre son derece yüksek stres değerleri gözlendi. Dikey ve oblik yükler altında spongioz ve kortikal kemikte titanyum modellerde PAEK modellerine göre daha düşük principal gerilim değerleri gözlendi.

SONUÇ: PAEK'ler implant çevresindeki kemiğe daha fazla stres aktardı. Titanyum modellerde stres dağılımı daha homojen iken PAEK'lerde stres implantların koronal kısmına komşu kemikte ve implant boynunda yoğunlaşmıştır.

ANAHTAR KELİMELER: Dental stres analizi, diş implantları, elastik katsayı, polimerler.