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Original Article

Stress analysis in implant, abutment, and peripheral bone with different restorative crown and abutment materials: A three-dimensional finite element analysis study

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ABSTRACT

Background: Stresses on prosthetic crown directly influences the survival rate of implants hence it should be considered while selecting prosthetic material.

The aim of the study is to evaluate stress analysis on implant, abutment and peripheral bone with change in different abutment and different crown materials by 3D finite element study.

Materials and Methods: A numerical procedure based on finite element method was adopted to investigate the influence of different prosthetic materials and abutment materials on stress situation. Eight different three-dimensional (3D) models of a bone-level implant system and an abutment were created by using the standard tessellation language (STL) data of original implant components. Combinations included of abutment materials i.e., Titanium (Ti), Polyetheretherketone (PEEK), Polyetherketoneketone (PEKK), Polymer infilterated hybrid ceramic (TZI) along with different restoration materials Monolithic Zirconia (MZ) and lithium disilicate glass ceramic (IPS e-max). In each model, the implants were loaded obliquely (150 N). The stress distribution in the implant, Abutment and peripheral bone was evaluated through the von Mises stress analysis.

Results: Higher stresses were found on neck of implants irrespective of abutment material and restorative material. Highest stress was found with PEEK material. The pattern of stress distribution in implant and peripheral bone was similar in all models.

Conclusion: There is no difference in stresses with the change in restorative material but the change in abutment material has effect on stresses on implants.

Key Words: Abutment, finite element analysis, implant, stress

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INTRODUCTION

Implant-supported prosthesis has become the treatment modality of choice for patients with missing teeth because of mechanical, biological, and esthetic advantages. The biomechanical behavior of implants is different from natural teeth due to the absence of periodontal ligament. The lack of periodontal ligament causes the occlusal forces to be directly transferred to the implant and surrounding bone in implant-supported dental prostheses. Biologically, this direct stress transfer could lead to bone loss in the peri-implant region. This would

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impact the long-term clinical success of the implant prosthesis.

Titanium (Ti) and its alloys have been the gold standard in abutment materials because of their favorable mechanical properties.[1] However, their grayish color and the possibility of corrosion and degradation render them less attractive when replacing teeth in the esthetic zone or where there is limited bone or soft-tissue support at the fixture platform junction.[2] With the advancement of more esthetic materials in dentistry, Ti has been replaced by other materials, i.e., polyaryletherketone (PAEK), resin-matrix ceramics, etc. PAEK is high-performance thermoplastics, having high strength and stiffness due to their chemical nature and good resistance to hydrolysis, and are, thus, suitable for extremely demanding conditions.[3] Polyetherketoneketone (PEKK) and polyether ether ketone (PEEK) are the two most prominent members of the PAEK family.

PEKK is a methacrylate-free thermoplastic high-performance polymeric material.[3] PEKK was first introduced by Bonner in 1962,[4] and since then, it has been used for different industrial and military purposes.[5] Recently, PEKK has increasingly been used as a biomaterial with properties suitable for applications in restorative, prosthetic, and implant dentistry.[6] Similar to PEKK, PEEK has an elastic modulus similar to bone and is, thus, believed to avoid high-stress transfer at the bone-implant interface as well as reduce the stress shielding effect on the bone.[7] Thus, led to the proposition of using both PEEK and PEKK as an alternate for Ti and its alloys.

Resin-matrix ceramics are composed of a highly filled organic matrix in an inorganic refractory material consisting of porcelain, glasses, and ceramics, followed by polymerization. Resin-matrix ceramics were introduced in dentistry because of the modulus of elasticity which is similar to dentin and their ease of milling by computer-aided design/computer-aided machining (CAD/CAM). These materials can be subcategorized based on the method of incorporation of ceramic into the polymer matrix as polymer-infused ceramic and resin nanoceramic.[8] Vita Enamic (VITA Zahnfabrik, Bad Sackingen, Germany) is a polymer-infused ceramic available as CAD/CAM blocks made of porous presintered feldspar ceramic network matrix infiltrated with organic polymer.[9] Industrial polymerization improves the monomer conversion and also enhances the mechanical properties.[9]

Regarding prosthetic crown materials, all ceramics are the material of choice in today's dental practice. Zirconia-based restorations have attained popularity because of their high esthetic potential and great biocompatibility. Zirconium dioxide has been a satisfactory material for implant-supported restoration for the last 10 years, but the most common failure is chipping of overlaying porcelain.[10,11] This has led to the development of monolithic zirconia (MZ), in implant restorations. Lithium-disilicate crowns have now emerged as an alternative to zirconia restorations because of their excellent esthetics and translucency. Thus, the possibility of having esthetic abutments with different prosthetic crown materials led to the hypothesis of the present study.

Three-dimensional (3D) finite element analysis (FEA) is a method to evaluate stress distributions in complex geometries such as implant-bone interfaces.[12] Finite element study also provides a platform for testing any new material in simulated clinical conditions. There are several studies about the use of different crown and abutment materials, but there is no literature available on resin-matrix ceramics as an abutment material. Thus, the aim of the present study was to evaluate the stress distribution at the peripheral bone (cortical and cancellous) and implant-abutment interface with different abutment and crown materials by FEA.

MATERIALS AND METHODS

A numerical procedure based on the finite element method was adopted to investigate the influence of different prosthetic materials and abutment materials on stress situations.

Finite element model

A Ti bone-level implant (AlphaBio 4.1 mm × 12 mm) was scanned along with Ti screw and standard Ti abutment to generate a standard tessellation language file for model formation. A 3D finite element model was created to simulate a Ti bone-level implant in the mandibular premolar region with 2-mm thick cortical bone. Abutment materials chosen for the study were Ti, PEEK, PEKK, and resin-matrix ceramics (VTE) (VITA ENAMIC), while prosthetic crown materials chosen were MZ and lithium disilicate (IPS e-max) [Table 1].

Eight different models were created to simulate different combinations of abutment materials and crown materials. Models were created with the help of Poisson's ratio and Young's modulus of elasticity for the materials given in the literature [Table 2]. Materials of all parts in the model were assumed to be homogeneous and isotropic. In addition, full implant–bone interface was established as complete osseointegration. The model was fixed in all degrees of freedom at the lower surface of the bone block.

FEA uses a complex system of points (nodes) and elements, which make a grid called mesh. The model in the present study consisted of 27,500 elements and 59,000 nodes. The mesh was programmed to contain the material and structural properties such as elastic modulus and Poisson's ratio, which define how the structure will react to certain loading conditions. Stress analysis was done using the structural stress analysis software program, ANSYS (Ansys, Inc.).

Loading and boundary conditions

The stress analysis was carried out by applying loads of 150 N (30°) of oblique load on the central fossa of the mandibular second premolar [Figure 1]. For each model, the von Mises' equivalent stress distribution was computed by the OptiStruct (optimization-enabled structural analysis) solver.

RESULTS

Various materials used in abutments and crown materials influenced the stress transfer at the

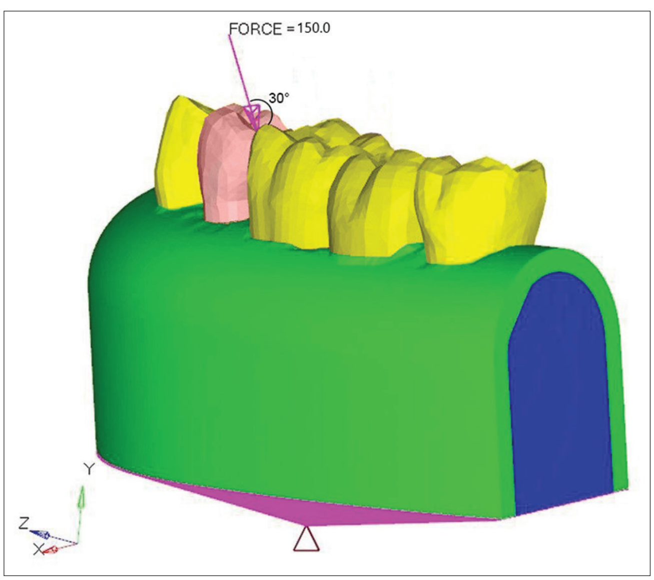

Figure 1: Schematic diagram showing loading condition on model.

abutment, implant, and peripheral bone. The stress patterns of each model are presented in Figures 2-5.

Stress distribution at abutment

Maximum von Mises stress value was found to be on the neck of abutment in all the models. The highest value of stress was found with Ti abutment, followed by resin-matrix ceramics and least with PEEK material as an abutment [Figure 2]. The restorative crown material was found to have no influence on the stress value of the abutment.

Stress distribution at cortical and cancellous bone

When stresses at peripheral bone were investigated, although there was no significant difference in the values, the maximum value of von Mises stress was found in the model of PEEK abutment with lithium-disilicate crown. The least value of von Mises stress in cortical bone was with Ti abutment [Figure 3]. A similar pattern of stress distribution was observed to be in cancellous bone [Figure 4].

There were more forces on cortical bone as compared to cancellous bone. On observation of cross-sectional

Table 1: Materials tested with manufacturer

Material	Product and manufacturer
Lithium disilicate glass-ceramic	IPS e.max CAD, Ivoclar Vivadent
MZ	Aidite, China
Titanium	Adin, Israel
PEEK	JUVORA Dental Disc; JUVORA Ltd.
PEKK	Pekkton Ivory (Cendres + matause, Switzerland)
Polymer-infiltrated hybrid ceramic	VITA ENAMIC; VITA Zahnfabrik

Materials used in the present study with their manufacturer details. PEEK: Polyether ether ketone; PEKK: Polyetherketoneketone; MZ: Monolithic zirconia

Table 2: Material properties used for model preparation[12]

Material	*Young's modulus (GPa)	**Poisson's ratio
Cancellous bone	13.7	0.30
Titanium implant	110	0.35
Titanium abutment	110	0.35
PEEK abutment	3.5	0.36
PEKK abutment	5.1	0.4
Polymer-reinforced hybrid ceramic abutment	30	0.23
Lithium disilicate	95	0.20
MZ	205	0.19
Resin cement	18.6	0.28

*Young's modulus (GPa); **Poisson's ratio for materials used in the present study to formulate a 3D model for FEA. PEEK: Polyether ether ketone; PEKK: Polyetherketoneketone; FEA: Finite element analysis; MZ: Monolithic zirconia; 3D: Three-dimensional

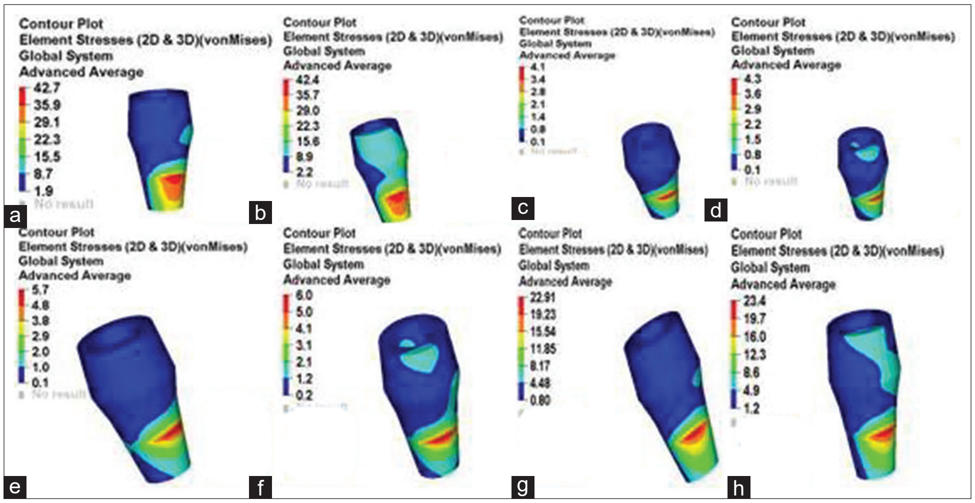

Figure 2: Stress at abutment: (a Ti-MZ, (b) Ti-IPS, (c) PEEK-MZ, (d) PEEK-IPS, (e) PEKK-MZ, (f) PEKK-IPS, (g) VTE-MZ, (h) VTE-IPS. TI: Titanium; MZ: Monolithic zirconia; PEEK: Polyether ether ketone; PEKK: Polyetherketoneketone; Represents IPS e-max- Brand name for E-max crowns, VTE-Vita enamic.

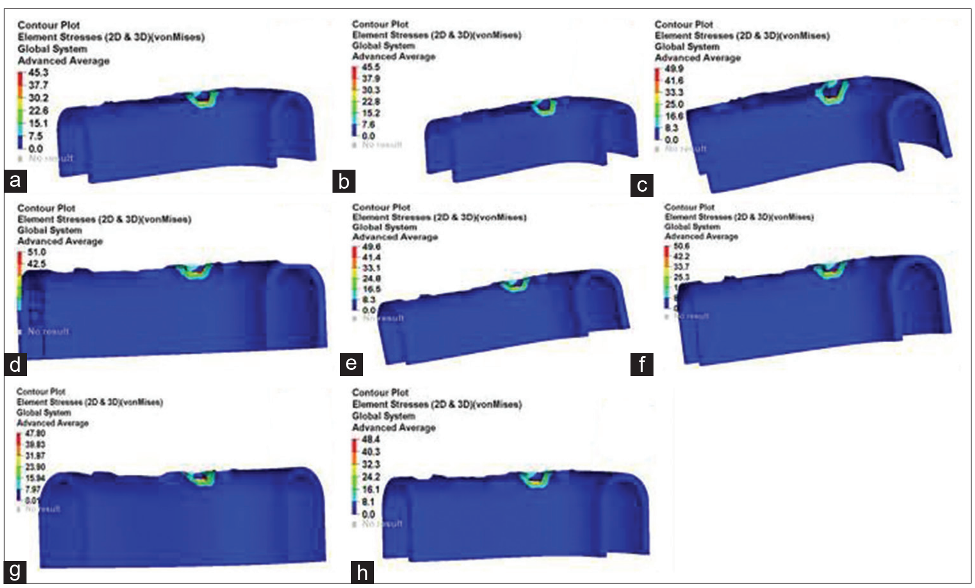

Figure 3: Stress at cortical bone: (a) Ti-MZ, (b) Ti-IPS, (c) PEEK-MZ, (d) PEEK-IPS, (e) PEKK-MZ, (f) PEKK-IPS, (g) VTE-MZ, (h) VTE-IPS. TI: Titanium; MZ: Monolithic zirconia; PEEK: Polyether ether ketone; PEKK: Polyetherketoneketone; Represents IPS e-max- Brand name for E-max crowns, VTE-Vita enamic.

of bone for stress evaluation, more stresses were found on the palatal side in all the models irrespective of crown and abutment materials [Figure 5].

Stress distribution at crown

Stress distribution for the crown was at the center of the central fossa in each model and change in abutment and prosthetic material did not influence the stresses of each model. The principal stress value was decreased at the buccal and lingual cusp. The maximum principal stress was 73.8 MPa with Ti abutment and lithium-disilicate crowns [Figure 6].

Stress distribution at implant

There were more forces at the neck of the implant in all models. Ti abutment showed a wide distribution of stresses on the implant compared to other abutment materials. There were no changes in the stresses with a change in crown material. Maximum stress was found with PEEK abutment material and least with Ti abutment [Figure 7].

DISCUSSION

The present study was conducted to evaluate the stress analysis with different abutments and prosthetic

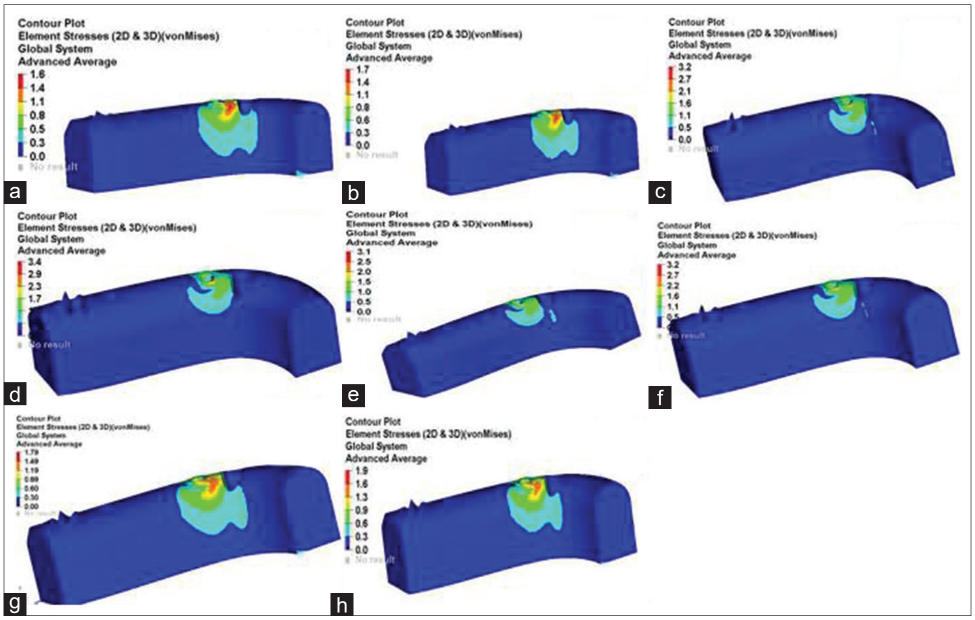

Figure 4: Stress at cancellous bone: (a) Ti-MZ, (b) Ti-IPS, (c) PEEK-MZ, (d) PEEK-IPS, (e) PEKK-MZ, (f) PEKK-IPS, (g) VTE-MZ, (h) VTE-IPS. TI: Titanium; MZ: Monolithic zirconia; PEEK: Polyether ether ketone; PEKK: Polyetherketoneketone; Represents IPS e-max- Brand name for E-max crowns, VTE-Vita enamic.

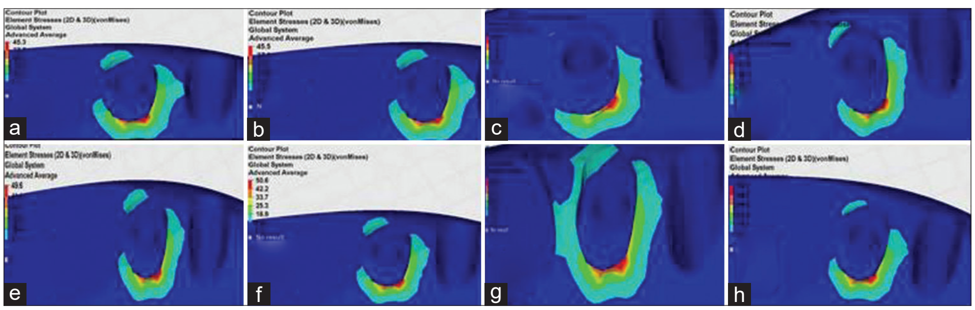

Figure 5: Cross section of stress at peripheral bone: (a) Ti-MZ, (b) Ti-IPS, (c) PEEK-MZ, (d) PEEK-IPS, (e) PEKK-MZ, (f) PEKK-IPS, (g) VTE-MZ, (h) VTE-IPS. TI: Titanium; MZ: Monolithic zirconia; PEEK: Polyether ether ketone; PEKK: Polyetherketoneketone; Represents IPS e-max- Brand name for E-max crowns, VTE-Vita enamic.

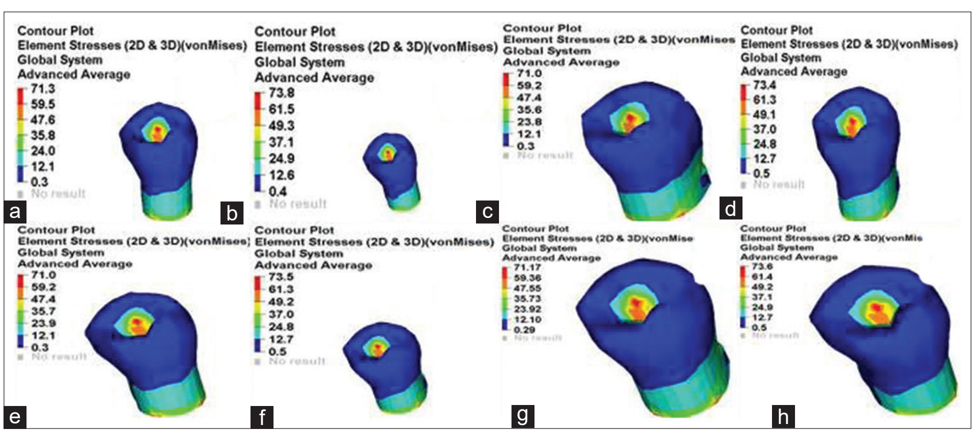

Figure 6: Stress at abutment: (a) Ti-MZ, (b) Ti-IPS, (c) PEEK-MZ, (d) PEEK-IPS, (e) PEKK-MZ, (f) PEKK-IPS, (g) VTE-MZ, (h) VTE-IPS. TI: Titanium; MZ: Monolithic zirconia; PEEK: Polyether ether ketone; PEKK: Polyetherketoneketone; Represents IPS e-max- Brand name for E-max crowns, VTE-Vita enamic.

crown materials. In recent times, finite element plays a prominent role in the assessment of stress in relation to implants.[13] Implant prostheses are retained by multiple components so determining

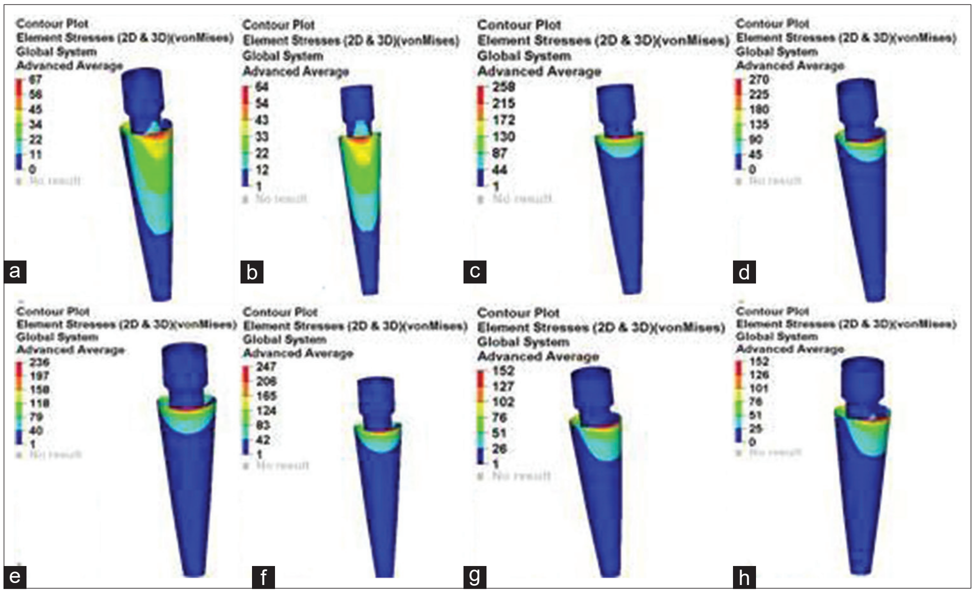

Figure 7: Stress at implant: (a) Ti-MZ, (b) Ti-IPS, (c) PEEK-MZ, (d) PEEK-IPS, (e) PEKK-MZ, (f) PEKK-IPS, (g) VTE-MZ, (h) VTE-IPS. TI: Titanium; MZ: Monolithic zirconia; PEEK: Polyether ether ketone; PEKK: Polyetherketoneketone; Represents IPS e-max- Brand name for E-max crowns, VTE-Vita enamic.

their biomechanical behavior is slightly difficult, but FEA is still a suitable analytical method for determining biomechanical behavior in complex structures. The results of the study revealed that all prosthetic materials and abutment materials had similar biomechanical behavior when it comes to stress distribution at abutment, crown, and peripheral bone. This was in accordance with other studies by Kaleli *et al*.[14] An FEA model can be 2D or 3D. In 2D models, out-of-plane deformations, strains, and stresses are insignificant, and artificial constraints result in more errors in the analysis. Therefore, the use of 3D models to analyze biological or biocompatible structures produces more realistic results than 2D models.

According to the literature, in implant-supported fixed prosthesis, the maximum occlusal force on the premolar is approximately 200–300 N.[15] Therefore, a mean oblique load of 150 N was selected at an angle of 30° from the vertical axis and pointed at the center of the occlusal surface of the crown. Additionally in previous studies, it has been proved that oblique load generates more stress.[16] On the evaluation of stress value on abutment with MZ or pressable ceramic as restorative crown material, Ti abutment material showed the greatest maximum stress, followed by resin-matrix ceramics followed by PEKK and the least with PEEK. Young's modulus, also known as elastic modulus, is one of the important deciding factors for a material's behavior. PEEK having the least Young's modulus among all the materials, distributed the load much more efficiently. Ti abutment developed maximum stress concentration on implant because it had the highest elastic modulus as compared to others. All materials showed the highest stress concentration in the implant neck area. Duan and Griggs[17] compared the stress distribution in lithium-disilicate ceramic and resin nanoceramic CAD/CAM crowns and reported that resin nanoceramic crowns showed lower stress values under vertical loading, but the difference was not substantial when the lateral component is added. However, in the present study, both prosthetic materials were analyzed with oblique loading and showed similar patterns of stress concentration.

In the present study, cement thickness was ignored as it has already been proved by Hojjatie and Anusavice[18] in their finite element study that cement thickness does not affect stress distribution.

On stress analysis with relation to implant, maximum stress value was found with PEEK abutment and minimum with Ti abutment around the neck of implant. Papavasiliou *et al*.[19] investigated the effect of the osseointegration degree to stress distribution and found higher crestal stresses than apical stresses under all conditions. In the present study, the stresses were concentrated in the neck of the implant due to the rigid connection between the implant and the bone. The modulus of elasticity of cortical bone is higher than spongy bone; for this reason, cortical bone is stronger and more resistant to deformation.[20]

On the assessment of maximum stress value on peripheral bone, there was no significant difference in stress value in cortical and cancellous bone with different combinations of abutment and restorative crown material. However, the maximum stress value was higher in the cortical bone than cancellous bone. Maximum stress value among different combinations was found with PEEK abutment and lithium-disilicate crown. The least value was observed with Ti abutment and lithium-disilicate crown. In the present study, it was observed that change in abutment material and prosthetic material did not affect much on stress value in the peripheral bone, which was in accordance with previous studies.[21] The reason may be that there are multiple components in the cementation of crown, for example, screw, cement layer, and abutment, which may dissipate the forces.

The strength of the present study was that recent materials were tested for combinations in implant-supported prostheses through a finite element study. However, there were some limitations of the present study as well, which included that only mandibular single unit implant was taken into consideration and the load was applied in the oblique direction. Although this was a 3D finite element study, it cannot simulate the clinical situation, so clinical studies with follow-up are required.

CONCLUSION

The following conclusions can be drawn within the limitations of the present study:

1. Prosthetic crown material does not affect the stresses in peripheral bone and crown in implant-supported prostheses
2. Maximum stresses were found on the neck of the implant body in all the models
3. There was the least stress on the implant with Ti as an abutment material, while on abutment least stress was caused by PEEK abutment material.

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Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial or non-financial in this article.

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