Dental Research Journal

Original Research

Stress distribution in bone around an implant-supported three-unit fixed dental prosthesis using two different computer-aided designing/computer-aided milling provisional crown materials: Milled polymethylmethacrylate and milled polyetheretherketone – A finite element analysis

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ABSTRACT

Background: Occlusal loading of osseointegrated implants is believed to be an essential determining factor in the long-term success of an implant treatment. Numerous studies have been conducted on the evaluation of stress distribution by definitive restoration materials for Implant-supported fixed prosthesis, but very few have evaluated provisional restoration materials for the same. This study aims to evaluate the influence of provisional restoration material – Milled Polymethylmethacrylate (PMMA) and Milled Polyetheretherketone (PEEK), over stress distribution on the peri-implant bone around an implant-supported three-unit, fixed dental prosthesis using finite element analysis method.

Materials and Methods: Three-dimensional models of a pair of bone-level implant system and titanium base abutments were created using the standard tessellation language data of original implant components. A bone block representing the mandibular posterior area was created, and the implants were placed in the bone block with 100% osseointegration in the 2nd premolar to 2nd molar region. A superstructure of an implant-supported 3-unit bridge was modeled on top of the abutments, each crown to be 8 mm in height and with an outer diameter of 6 mm in 2nd premolar region and 10 mm in 1st molar and 2nd molar region. Two different models were created according to combinations of provisional restoration materials, namely, Milled PMMA and Milled PEEK based on. In each model, the implants were loaded vertically (300 N) and obliquely (150 N at 30°). The stress distribution in the cortical bone, cancellous bone, and implant was evaluated through the von Mises stress analysis.

Results: The results showed no difference in stress distribution due to the different provisional restorations – Milled PMMA and Milled PEEK. In addition, the vertical load resulted in higher stress values in the implant components, cortical bone, and cancellous bone in both PEEK and PMMA models as compared to oblique loading.

Conclusion: The new polymer, PEEK was seen to provide comparable stress generation in the current study without exceeding the physiological limits of peri-implant bone. Thus, it can be

Received: 03-May-2022
Accepted: 26-Sep-2022
Published: 28-Mar-2023

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Website: www.drj.ir
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www.ncbi.nlm.nih.gov/pmc/journals/1480

How to cite this article: Barua SL, Poduval TS, Rani S, Jain N, Thakur S. Stress distribution in bone around an implant-supported three-unit fixed dental prosthesis using two different computer-aided designing/computer-aided milling provisional crown materials: Milled polymethylmethacrylate and milled polyetheretherketone – A finite element analysis. Dent Res J 2023;20:33.

considered as a good alternative to PMMA resin as a provisional crown material since it provides certain additional benefits.

Key Words: Finite element analysis, implant dentistry, polyetheretherketone, poly methyl methacrylate, provisionalization

INTRODUCTION

Successful long-term results of dental implants have led to an increase in their usage in many clinical situations.[1] The biomechanical factors affecting the stress and strain fields around osseointegrated dental implants are numerous, including type of loading, material properties of the implant, and the prosthesis.[2] Occlusal loading of osseointegrated implants is believed to be a very important determining factor in the long-term success of an implant treatment program. Overload can cause bone resorption or fatigue failure of the implant whilst under load may lead to disuse atrophy and subsequent bone loss as well.[3]

Provisional restorations are used as an intermediate stage for short- or long-term placement on the dental implant between the time of surgical placement of the implant until the definitive restorations are fabricated and placed once the implant has completely osseointegrated.[3] The performance of individual provisional restorations varies and depends on the differences in material properties achieved by the various fabrication techniques.[4]

Using computer-aided design/computer-aided manufacture (CAD/CAM) technology to fabricate restorations has gained popularity in comparison with conventional techniques recently. It has been reported that CAD/CAM provisional crowns are stronger and exhibit better marginal accuracy than directly fabricated provisional restorations, especially following thermal cycling.[4] Currently, for provisional restorations, many manufacturers offer high-density polymers based on highly cross-linked resin-based materials (composites, polymethylmethacrylate [PMMA]) for CAD/CAM manufacturing methods.[5]

As implant-supported fixed prostheses are more prone to occlusal overloading than tooth-supported crowns due to the missing of the physiological semi-elastic connection (periodontal ligament) and the tactile sensitivity, the application of brittle materials may cause numerous *in vivo* complications such as fracture or chipping.[6] To overcome or minimize the risk of fracture, resin-based materials with improved shock absorbing capacity may be preferred. However, acrylic resins do not offer a sufficient abrasion resistance to allow a stable occlusal relationship.[7]

A new polymeric material in this field is polyetheretherketone (PEEK) - a polymer from the main group polyaryletherketone. It is a high-performance thermoplastic polymer. Young's modulus of elasticity and tensile properties are close to human bone, enamel, and dentin. Despite of significantly low elastic moduli and hardness, abrasive resistance of PEEK is comparable to that of metallic alloys.[8]

Although various methods for the evaluation of stress around dental implant system such as photoelastic method and strain measurement are available but finite element method offers several advantages, including accurate representation of complex geometries, easy model modification, and representation of the internal state of stress. This method presents a suitable degree of reliability and accuracy "without the risk and expense of implantation."[9]

Although many studies have been conducted on the evaluation of stress distribution by definitive restoration materials for implant-supported fixed prosthesis, very few have evaluated provisional restoration materials for the same. Thus, the purpose of this study is to evaluate the influence of provisional restoration material – Milled PMMA and Milled PEEK, over stress distribution on the peri-implant bone around an implant-supported three-unit fixed dental prosthesis using finite element analysis method.

The null hypothesis for the study is that there is no significant difference in the stress distribution in bone around an implant-supported three-unit fixed dental prosthesis using different CAD/CAM provisional crown materials – Milled PMMA and Milled PEEK.

MATERIALS AND METHODS

For this study, a three-dimensional finite element model was generated of 2 threaded dental implants of the above-mentioned dimensions embedded in homogeneous cancellous bone surrounded by a 2-mm-thick cortical layer in the region of 2nd mandibular premolar and 2nd mandibular molar, respectively. The 3D model of the implant in the bone structure was considered to be with 100% osseointegration and the gingiva was ignored for all models.

A titanium bone-level implant (Alpha BiocareMultineo System – Internal Hex Connection [HI]; Alpha Bio Tec Ltd, Washington, D. C, U. S. A) 4.2 mm in diameter and 10 mm in length, a titanium base abutment (Alpha Biocare Multineo System Straight Abutment; Alpha Bio Tec Ltd, Washington, D. C, U. S. A) 4.7 mm in diameter and 5 mm in height, and their inner screws were scanned with an optical scanner (Activity 880; Smart Optics Sensortechnik GmbH) to create corresponding CAD models using reverse engineering technique. The standard tessellation language data of each component were transferred into three-dimensional (3D) modeling software (Solidworks 2019 Premium; Dassault Systèmes).

To simulate a fixed prosthesis, a superstructure was overlapped over the titanium abutment screwed over the implants. A superstructure of an implant-supported three-unit bridge was modeled on top of the abutments, each crown to be 8 mm in height and with an outer diameter of 6 mm in 2nd premolar region and 10 mm in 1st molar and 2nd molar region. These dimensions were chosen to roughly correspond to the size of the posterior teeth, which were replaced by the implant-supported prosthesis [Figure 1].

A discretization process with 10 nodes of quadratic tetrahedral elements was conducted for all 3D models using meshing software (HYPERMESH; Altair University). A total of 67988 nodes and 279384 elements were used for each model. The meshed models were transferred to theFEA software (ANSYS Standard Solver; ANSYS Inc.) for stress distribution analyses. All models were considered homogeneous, isotropic, and linearly elastic.

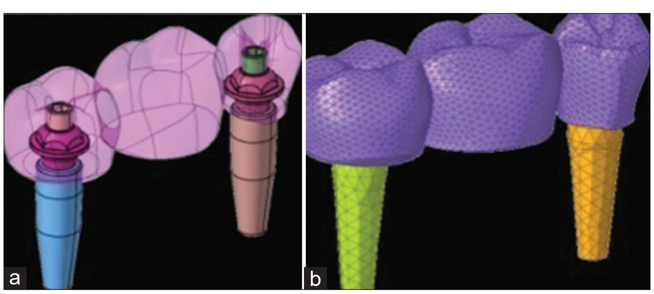

Figure 1: Model of 4.2 × 10 Alpha Biocare Implants with three-unit screw retained fixed prosthesis superstructure (a) CAD Model (b) Mesh Model. CAD: Computer-aided design.

Two different restorative materials, i.e., Milled PMMA and Milled PEEK, were tested in terms of stress distribution. The Young modulus and Poisson ratio of each material were based on the information from the manufacturer and past literature [Table 1]. The constraints were set to no movement in the x, y, and z axes at the mesial and distal exterior surfaces of the bone structure. Two different models were created according to restorative materials.

In each model, 300 N of the vertical load was applied to the central fossa, and 150 N of oblique load (30°) was applied to the buccal incline of the palatal cusp. The stress distribution in the implants, abutments, and restorative provisional were evaluated using the von Mises stress (maximum equivalent bone stress) analysis [Figure 2].

RESULTS

The results of the von Mises stress analysis are presented in Figures 3 and 4. The vertical load resulted in higher stress values in the implant components, cortical bone, and cancellous bone in both PEEK and PMMA models.

Table 1: Properties of modelled materials

Materials	Young's modulus (MPa)	Poisson's ratio
Implants (Ti), abutment (Ti) and abutment screw (Ti)	110,000	0.32
PMMA	5000	0.34
PEEK	4000	0.37
Cortical bone	14,800	0.30
Cancellous bone	1340	0.30

PMMA: Polymethylmethacrylate; PEEK: Polyetheretherketone

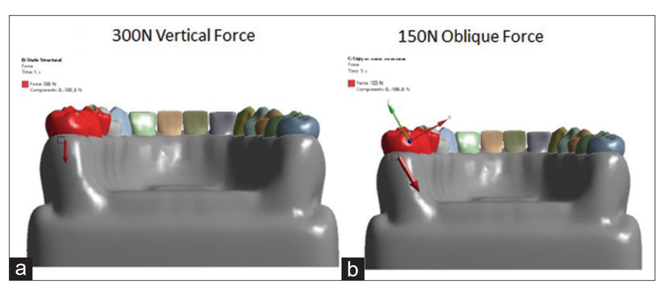

Figure 2: Loading conditions. (a) Vertical Forces (b) Oblique Forces.

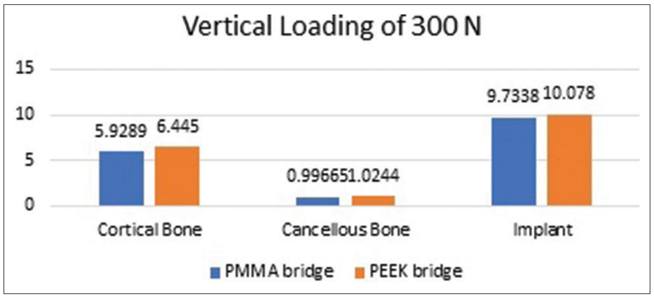

Figure 3: Stresses seen in cortical bone, cancellous bone and implant under vertical loading in MPa. MPa: Mises equivalent stress.

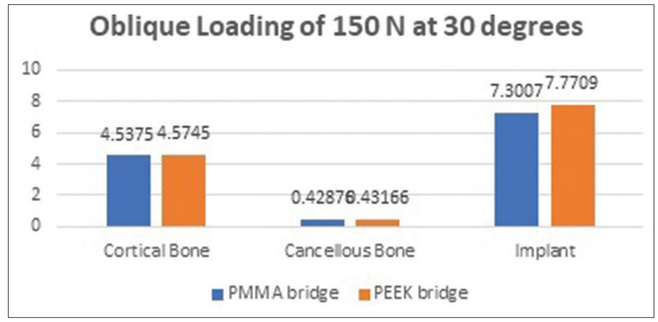

Figure 4: Stresses seen in cortical bone, cancellous bone and implant under oblique loading in MPa. MPa: Mises equivalent stress.

Under vertical loading, the overall stress generation in the both the models was seen to be similar [Figure 5]. The pattern of stress generation was also found to be similar in both the models with the highest stresses on the distobuccal cuspal inclines of 1st molar and mesiobuccal cuspal inclines of 2nd molar for the PMMA model while on the distobuccal cuspal inclines of 1st molar and buccal surface of 2nd molar for the PEEK model. In the cortical bone, the stress generation within cortical bone was seen higher in the PEEK model than in the PMMA model. Stress concentration was seen to be highest toward the apical region in lingual and buccal surfaces of 1st and 2nd molar in the PMMA model. On the other hand, the cortical bone in the PEEK model showed more stress concentration in the apical region of the buccal and lingual surfaces of 2nd molar. The stress generation within cancellous bone was seen within similar ranges for PMMA and PEEK models with maximum stress concentration towards the occlusal region of 2nd molar. Within the implant, the stress generation within the implant was seen higher in the PEEK model than in the PMMA model with the most stress concentration both the models in the neck of the implant of the 2nd molar region.

Under oblique loading, the overall stress generation was found to be similar in both the models with maximum deformation on the mesiolingual and distolingual cusps and distobuccal cusp of 1st molar and mesiolingual cusp of 2nd molar for the PMMA model while it was seen on the lingual cusp tip of 2nd premolar, lingual cuspal inclines of 1st molar and mesiolingual cusp and lingual fossa of 2nd molar in the PEEK model [Figure 6]. The stress generation within cortical bone was seen to be almost equivalent in both models with PMMA model showing more stress concentration toward the apical region of the lingual plate of 2nd molar. On the other hand, the cortical bone in the PEEK model showed more stress concentration towards the apical region of the lingual plate of 1st and 2nd molar. Even within the cancellous bone, the stress concentration bone was seen within similar ranges for both models. The cancellous bone in PMMA model showed more stress concentration toward the cervical region of the lingual plate of 2nd molar while in the PEEK model, more stress concentration was seen toward the cervical region of the lingual plate of 1st and 2nd molar. The stress generation within the implant was also found to be similar for both the models with the most stress concentration for both the PMMA and PEEK models at the neck of the implant of the 2nd molar region.

DISCUSSION

The rehabilitation of the posterior edentulous mandibular area is a topic that deserves meticulous prosthesis selection as it is a region which tolerates most of the masticatory load.[1] Thus, in the present study, the mandibular posterior region was chosen as the area of interest for evaluating the stress generation in the bone. In tooth-supported fixed partial dentures, the periodontal tissue acts as a shock-absorbing mechanism and allows stress distribution to supporting bone. However, in implant-supported fixed partial dentures, the stresses occur as a result of functional forces directly transmitted to the supporting bone by restorative material, abutment, and implant.[10]

The effect of provisional restoration materials is of very critical value as it provides loads on the implant during the delicate phase of osseointegration but very sparse literature is available on the same. Thus, this study was undertaken to understand the stress generation due to such provisional restoration materials on the bone and implant.

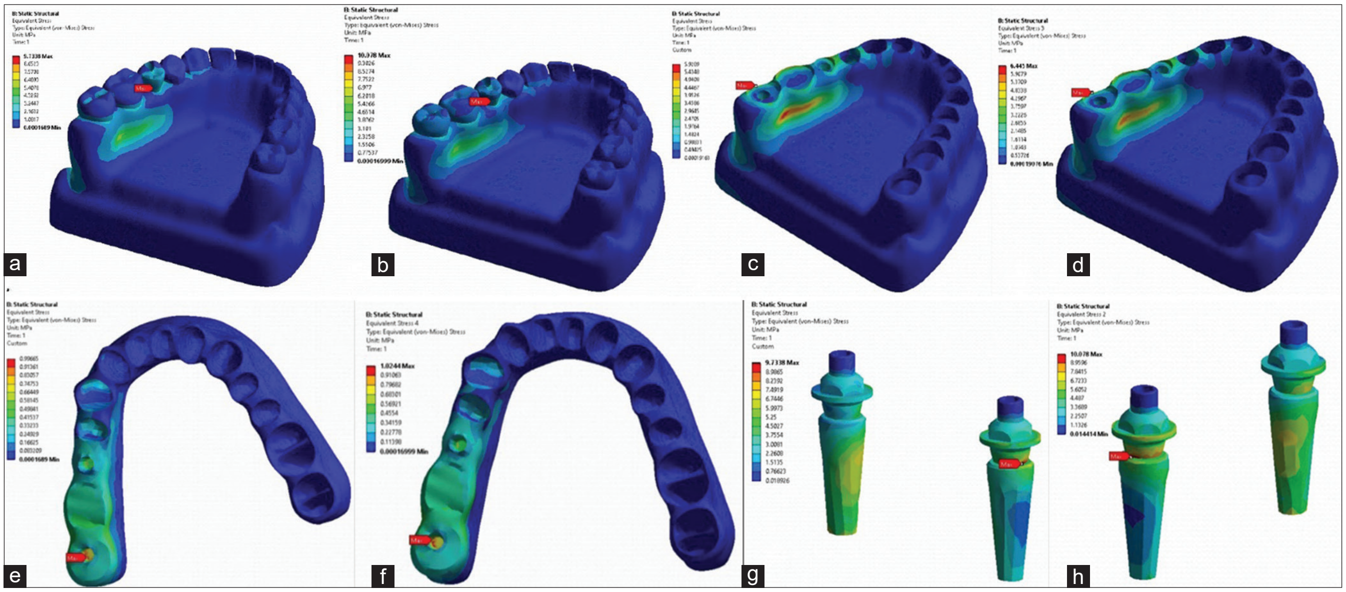

Figure 5: Stress Generation under vertical force (a) Overall Stress Generation in PMMA model, (b) Overall Stress Generation in PEEK model, (c) Stress Generation in Cortical Bone in PMMA model, (d) Stress Generation in Cortical Bone inPEEK model, (e) Stress Generation in Cancellous Bone in PMMA model, (f) Stress Generation in Cancellous Bone in PEEK model, (g) Stress generation within implant in PMMA model, (h) Stress generation within implant in PEEK model. PMMA: Polymethylmethacrylate; PEEK: Polyetheretherketone.

A new polymeric material, PEEK emerged that can be used an alternative to PMMA for CAD-CAM provisional restorations. Its biocompatibility and bio-stability are supported by the US Food and Drug Administration Drug and Device Master files. It also has the added advantage of its low specific weight which can be used to construct very lightweight prosthesis which will provide high patient satisfaction and comfort.[11] Being a soft and ductile material, PEEK can yield nicely and adapt well resulting in a good marginal fit.[12] Thus, the present study attempted to evaluate the difference in stress generation in the bone due to Milled PMMA provisional and Milled PEEK provisional.

There are no explicit guidelines in literature for interpreting the results of stress analysis, nor are there any suggestions regarding the kind of stresses that must be used in the analyses. Chen and Xu *et al*. (1994),[13] emphasized that the value of FE modeling is in relative values calculated at distribution pattern rather than quantitative values.

Almost equivalent stress generation was seen in the PEEK model as compared to the PMMA model under vertical forces of 300N with a slightly higher value for the PEEK model. This is in accordance with Papavasiliou *et al*. (1997)[10] who observed no differences in stress generation between occlusal materials. Similarly , Bassit, Lindsrom, and Rangerty (2002)[14] also demonstrated that using different occlusal surface materials does not produce different stresses in implants. Cibrika *et al*., (1992)[15] did not observe a significant statistical difference when they used resin, gold, and ceramic as occlusal surfaces. The reason for the slight discrepancy seen in the current study may result from the differences between materials used in the current study and the other studies. A possible reason for greater stress generation due to PEEK restoration could be the fact that it has a lower modulus of elasticity than PMMA. This implies that it is slightly less resistant to bending forces and thus creates more stresses in the underlying structures.

In the present study, it was observed that the largest stress concentration in the bone was situated in the outer cortical layer of bone located in the thin bone plates buccally and lingually to the implant. This was in accordance with the observations made by other authors such as Soltesz *et al*. (1982)[12] and Borchers *et al*. (1983)[13] where the highest stress concentrations around a dental implant were observed in the crestal region of the cortical bone. This observation was not surprising, because the largest stress is often found near structure surfaces.[16]

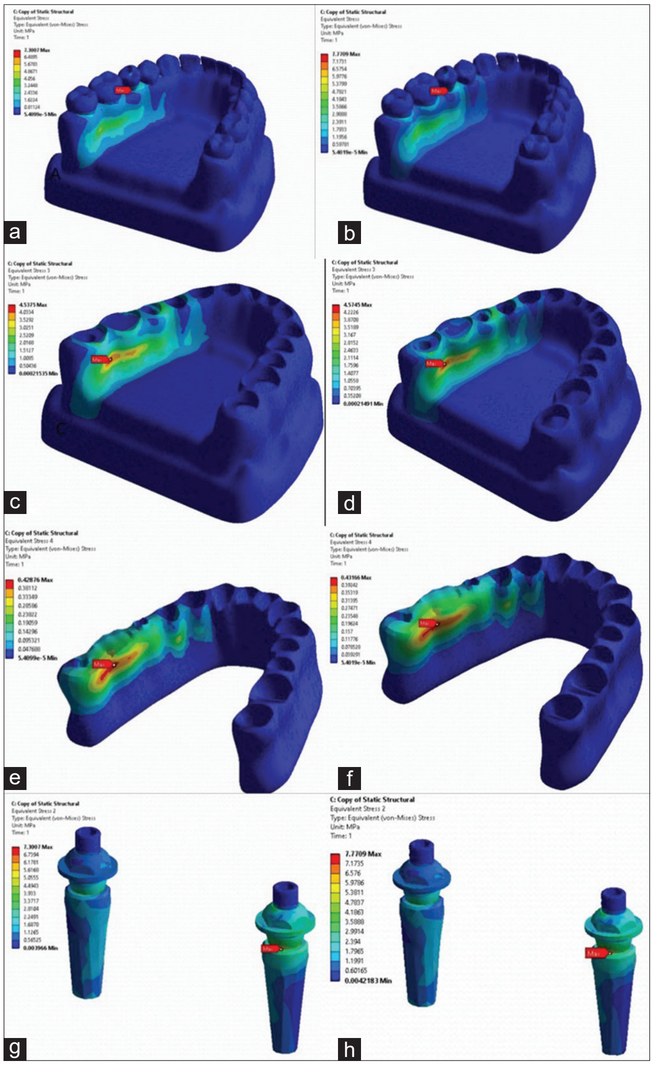

Figure 6: Stress Generation under oblique force (a) Overall Stress Generation in PMMA model, (b) Overall Stress Generation in PEEK model, (c) Stress Generation in Cortical Bone in PMMA model, (d) Stress Generation in Cortical Bone in PEEK model, (e) Stress Generation in Cancellous Bone in PMMA model, (f) Stress Generation in Cancellous Bone in PEEK model, (g) Stress generation within implant in PMMA model, (h) Stress generation within implant in PEEK model. PMMA: Polymethylmethacrylate; PEEK: Polyetheretherketone.

When stress generation in cortical bone was comparatively evaluated for Milled PMMA and Milled PEEK restorations, it was observed that there was greater stress generation in the PEEK model rather than PMMA model. Since modulus of elasticity is higher in PEEK, its ability to transfer and dissipate occlusal forces might be less than that of PMMA. Similar results were obtained by Rosentritt *et al*.[17] in their *in vitro* study that investigated the force absorption capacity of implant-supported crowns made of different restorative materials and found that PMMA and PEEK crowns both had similar shock absorbing capacity as compared to materials with higher modulus of elasticity such as titanium and ceramics.

When it came to the cancellous bone, the present study showed that higher stress was generated toward the occlusal region of the bone, especially on the distal side. The highest stress generation in cancellous bone, irrespective of the type of crown material was 1.02 Mises equivalent stress (MPa) which is less than the yield strength of soft bone, i.e., 2 MPa.[18] The stress generation in cancellous bone in both PEEK and PMMA models were very similar irrespective of loading direction. The lower elastic modulus of both resins results in lowered resistance to deformation, thus producing a larger bending of the prosthesis toward the pontic. This is consistent with the results obtained in a study conducted by Sevimay and Turhan.[19] Who concluded that higher stress magnitudes were seen in D3 and D4 bone as the trabecular bone is weaker and there is less resistance to deformation than in the other bone qualities modeled.

In the present study, between bone and the implant, significantly greater stress generation was seen in the implant. It is noteworthy that, the stresses generated were still well below the yield strength of titanium, i.e., 880 MPa. According to the rigid connection between implant and bone, stress was generated in the neck of the implant and was similar to previous studies by Motta *et al*.[20] and Ghasemi *et al*. (2014).[21] The greater stress generation in this location may be explained by the discrepancy in stress distribution caused between the bending mandible and static abutments under vertical load.

The null hypothesis that there would be no difference in stress distribution in bone around an implant-supported three-unit fixed dental prosthesis using different CAD/CAM provisional crown materials – Milled PMMA and Milled PEEK was thus, accepted.

The limitations of the study were that the properties of the components were considered to be homogeneous and isotropic and 100% implant-bone interface was established, which does not necessarily simulate clinical situations.[16]

Clinical implications of the study

The new polymer, PEEK was seen to provide comparable stress generation in the current study without exceeding the physiological limits of peri-implant bone. Thus, it can be considered a good alternative to PMMA resin as a provisional crown material since it provides the additional benefits of better surface resistance to chemicals, lower water solubility, and higher abrasion resistance to mechanical wear as compared to PMMA resin.

CONCLUSION

Within the limitations of the study, the following conclusions were drawn:

1. Vertical load resulted in high stress concentrations
2. The change in restoration material did not affect the stress distribution in neither the implants nor the peripheral bone.

Financial support and sponsorship

Nil.

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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