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Stress Distribution on Solitary Implants Restored with Four Different Materials in the Posterior Maxilla - A Three-Dimensional Finite Element Analysis

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Abstract

Introduction: The aim of this research is to evaluate and compare the stress distribution pattern generated within the implant, at the implant - bone interface and the surrounding bone with solitary implants in the maxillary first molar region when restored with monolithic Zirconia, Polyether Ether Ketone (PEEK®), Zirconium silicate (Ceram age®) and Cobalt-Chromium crowns.

Materials and methods: In this study finite element methodology was used to study the stress patterns in a single implant restored with 4 different materials when oblique and vertical loads are applied. All four CAD models were created using SOLIDWORKS software and then converted into a mesh model by Hyper mesh and the final analysis was conducted by ANSYS analysis software by loading at vertical axis and offset loading with a load of 200 N and 100N.

Results: Maximum principal stress is observed in Cr-Co (2525MPa) on applying oblique load and in Zirconia (2169.3 MPa) when applying vertical load and least amount of stress observed in Ceram age (466.76MPa &

2040.2MPa). Von-mises stress observed maximum in Cr-Co (3539.6MPa) and least in PEEK (1221.8MPa) when oblique load of 100N applied on the crown. Similarly, this stress was observed maximum in Cr-Co (3539.6MPa) and least in PEEK (1170.3MPa) whole bodily when 100N oblique load is applied.

Conclusion: All four restorative materials are taking up the vertical load similarly, but when oblique load is applied there is a significant difference between maximum stresses taking up by each structure. PEEK, Ceram age showed least amount of stress in crown and whole body when compared with Cr-Co and zirconia.

Keywords: FEA, Implants, stress, Zirconia, PEEK, Ceram age, ANSYS

Introduction

Edentulism accounts for more than a third of the global oral disorder disability burden. (1) It has been established that edentulous status has a detrimental impact on oral health-related quality of life. Clinicians are confronting an increasing need to provide solutions to this population because to a rise in their life expectancy, as well as create prosthesis that replace natural teeth, allowing for maximum satisfaction and enhanced quality of life. (2) Dental implants have been the most popular treatment option due to their high success rates in restoring lost aesthetics and function. Since the advent of osseointegration, dental implants have swiftly advanced, eventually replacing removable dentures in the treatment of partially or fully edentulous patients (3). Osseointegration, which histologically is defined as 'direct bone-to-implant contact', is believed to provide rigid fixation of a dental implant within the alveolar bone and may promote the long-term success of dental implants. (4)

Because implants lack periodontal ligaments and are in direct contact with bone, they exhibit biomechanical behaviours that differ from natural teeth. As a result, the implant's occlusal loads are directly transferred to the surrounding bone structure. (5,6) This relationship has an impact on the stress distribution in implants and surrounding bone, which is one of the most important variables in implant success. The direction of loading, the design, and the material qualities of the implant or restorative crown all influence the stress or energy transfer between the implant and peripheral bone. (7)

The reaction of the cells and matrix to the material surface, as well as the mechanical restrictions in the proximity of the implant, determine the bone response on the implant surface. The type of loading, the bone-to-implant interface, the length and diameter of the implants, the form and properties of the implant surface, the prosthesis type, and the quantity and quality of the surrounding bone all influence load transfer from implants to the surrounding bone. (8,9)

Different materials have been developed in recent years to meet various therapeutic conditions. Because of its superior aesthetic appearance and metal-free structure, all-ceramic restorations are becoming increasingly popular. This aspect has heightened awareness of the importance of improving the strength and reliability of ceramic systems. (10) Photo-elastic Study, Finite Element Analysis, and Strain Measurement on the Bone Surface are some of the approaches used to assess stress around the dental implant system.

Finite Element Analysis (FEA) has been used extensively to predict the biomechanical performance of various dental implant designs and the effect of clinical factors on implant success. It has a number of advantages, including accurate representation of complicated geometries, model change ease, and representation of the internal state of stress and other mechanical properties. (11) By understanding the basic theory, method, application, and limitations of FEA in implant dentistry, the clinician will be better equipped to interpret the results of FEA studies and extrapolate these results to clinical situations. (12)

FEA is a technique for obtaining a solution to a complex mechanical problem by dividing the problem domain into a collection of much smaller and simpler domains or elements in which the field variables can be interpolated using shape functions. In recent times, image-based approaches combined with FEA have allowed effective stress-strain investigations in dental implantology. (8) An overall approximated solution to the original problem is determined based on variational principles. In other words, FEA is a method whereby, instead of seeking a solution function for the entire domain, one formulates the solution functions for each finite element and combines them properly to obtain the solution to the whole body. Because the components in a dental implant-bone system are extremely complex geometrically, FEA has been viewed as the most suitable tool for analyzing them. (13)

Stresses of many kinds are employed in FEA studies to assess mechanical stress in the peri-implant bone, including von Mises stress, the maximum, the least primary stress, and the maximum shear stress. The von Mises stress is the most widely used scalar-valued stress invariant for evaluating yielding and failure behaviour of diverse materials. The maximum principal stress is useful for measuring tensile stress, while the minimum indicates compressive stress. Because bone possesses both ductile and brittle qualities, principal stress is an excellent choice for these experiments. (14)

The aim of this research is to determine to which crown and implant combination is better in minimizing the amount of stresses transferred to the surrounding bone to ensure a high success rate of osseointegration.

Materials and methods

The study was performed in Department Prosthodontics, crown & bridge and implantology, Mahe Institute of Dental Sciences and Hospital, Puducherry, India. The study was performed to determine stress distribution patterns within the implant, at the implant-bone interface, and the surrounding bone at the maxillary molar region in a single implant with 4 different crown materials which were subjected to loading in 2 different angulations.

Finite element analysis

The various steps involved in the fabrication of the Finite Element Model (FEM) were: -

1. Construction of geometric model.
2.Construction of finite element model from a geometric model.
3. Assigning material properties.
4. Defining the boundary conditions.
5. Application of forces.
6. Execution of analysis and interpretation of Results

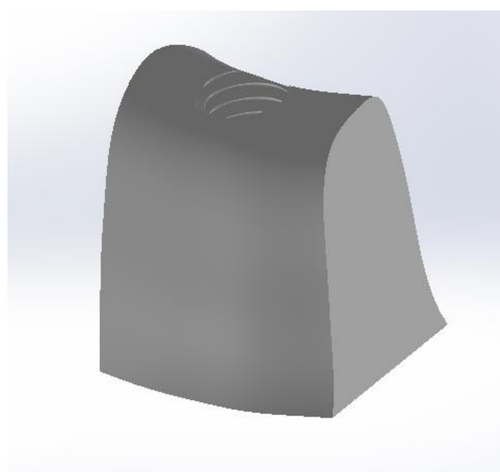


Figure 1: Bone Model

1) Construction of geometric model.

(a) Modelling of the maxillary molar segment

The maxillary posterior bone structure for the study was developed from sequential computed tomography (CT). The CT scan image in DICOM format (Digital Imaging and Communications in Medicine) were used as the input and were imported to MIMICS (materialize's interactive medical image control system). MIMICS is a medical modelling software used for the visualization and segmentation of CT/MRI images. It is a professional medical imaging processing tool for 3D modelling and designing. The imported data was used to create the 3D surface model of the teeth. This model is exported as STL (Stereolithography) format and imported into Rapid Form software (2004) to convert cloud data points to surfaces (points, splines, lines, and surfaces).(49,50)

Modelling of implant

Nobel Replace tapered implant (Nobel BioCare, Kloten, Switzerland) with 4.3 mm diameter and 10 mm length is scanned using a 3D scanner. This model was exported in STL (Stereolithography) format. The long axis of the implant is perpendicular to the crest of the ridge.(7)

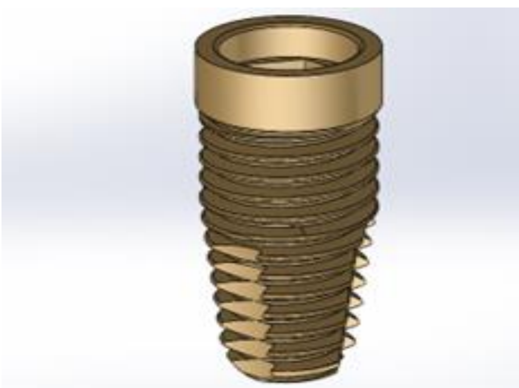


Figure 2: implant model

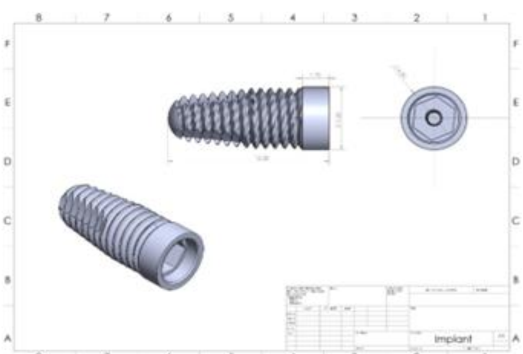


Figure 3: Draft Model of implant with dimensions

c) Modelling of the crown

3D geometric model of the crown is made using SOLIDWORKS software and all models were imported to IGES format.

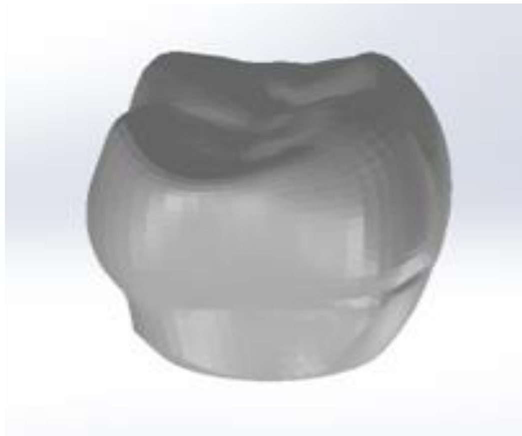


Figure 4: Crown model

Figure 5: Final assembled model

2) Construction of finite element model from a geometric model.

The model was defined in IGES (Initial Graphics Exchange Specification) format and then fully rendered to the ANSYS software for analysis. The geometric model of implant and associated structures were imported into the meshing software "Hyper mesh".

Hyper mesh software was used for converting the geometric model into a finite element model, which had the advantage of maximizing product performance, automating design processes, and improving profitability within an open and flexible environment. Advanced automation tools within Hyper mesh allow the users to optimize meshes from a set of quality criteria, change existing meshes through morphing and generate mid-surfaces from models of varying thickness. Meshed models were called finite element models and they consisted of 3D four noded tetrahedral elements.

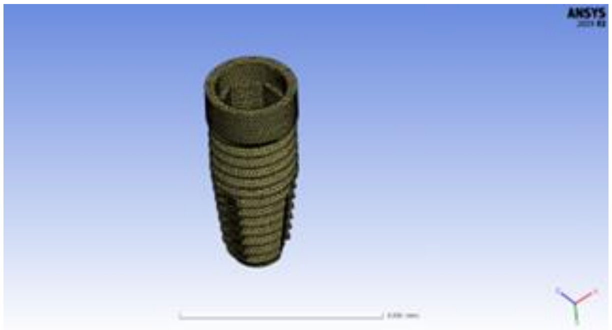


Figure 6: Implant mesh

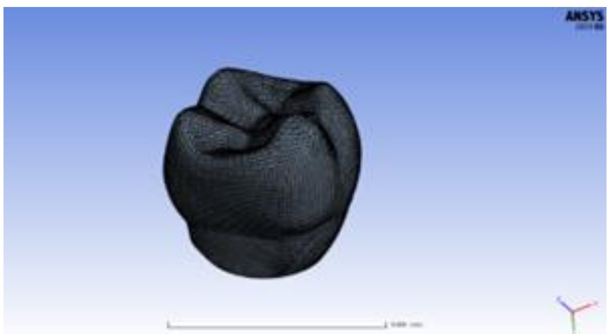


Figure 7: Crown mesh

3) Assigning material properties

The parameters and material properties should be precise and accurate to obtain reliable results in a patient-based study. Obtaining correct parameters can be a hard task and much estimation needs to be done when there was limited data available either from material testing or from literature. The material properties assigned were the Young's Modulus (or modulus of elasticity) and the Poisson's Ratio. By assigning a set of material parameters to the finite element software, one can readily obtain a set of numeric results. The point of force application, the magnitude, and the direction of force application can easily be varied to simulate the clinical situation. Young's modulus and Poisson's ratio of the materials will be assigned to each solid component with isotropic, homogeneous, and linearly elastic behaviour (51) The information of Young's modulus and Poisson's ratio are selected from the literature.(8,12,47,51–54) The analysis was done in ANSYS Mechanical APDL. The model used in this study involves several assumptions.

4) Defining the boundary conditions

The meshing was done and a tetrahedral element was used in the study. The outer surface of the maxillary bone was fixed (all displacements are restricted) in buccal and palatal surfaces as the boundary conditions.

5) Application of forces

Loading of an implant three-dimensionally had to be done with a normal occlusal force (200N axial load, 100N oblique load) The axial load was distributed to the central fossa of the maxillary first molar. Whereas the oblique load was distributed onto the buccal incline of the palatal cusp.

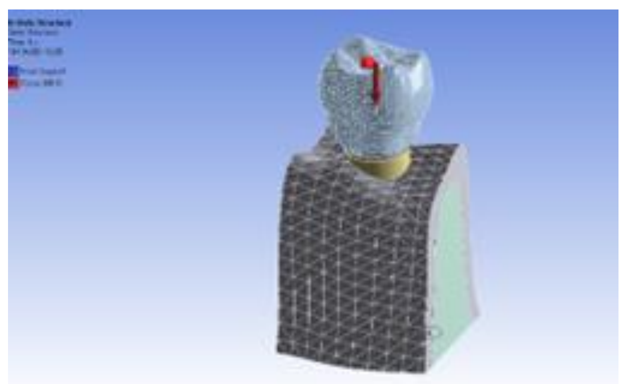


Figure 8: vertical loading

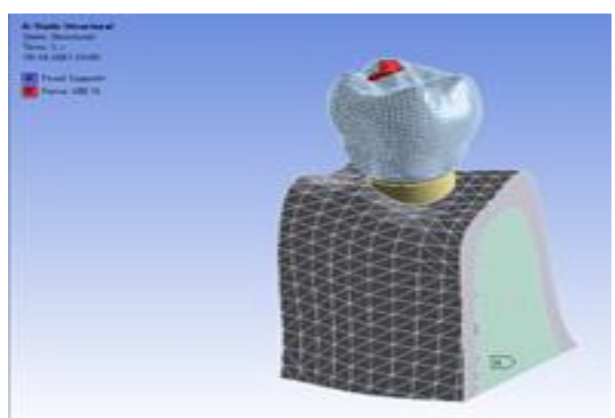


Figure 9: oblique loading

6) Execution of analysis and interpretation of results

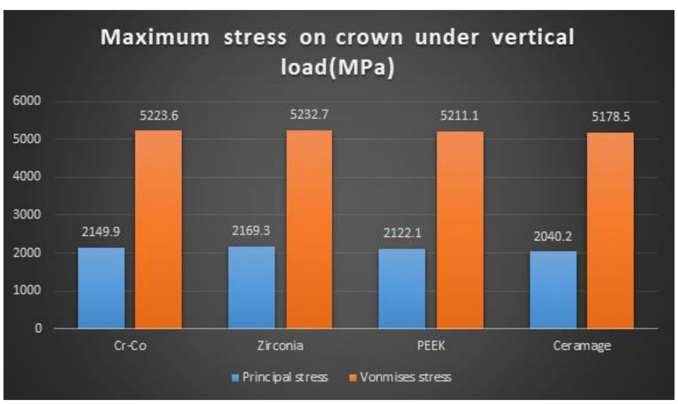
The linear static analysis was carried out using the ANSYS software (Analysis System Software version 19.2) and the responses of applied loads were interpreted. ANSYS - A finite element analysis (FEA) code widely used in computer-aided engineering that allowed us to construct computer models of structures, machine components, or systems; apply operating loads and other design criteria; and study physical responses, such as stress levels, temperature distributions, pressure, displacement, etc.

It helps in obtaining accurate numerical solutions used to predict the response of physical systems that are subjected to external stress. In this study, the FEM results are presented in terms of Principal stress values and displacement.

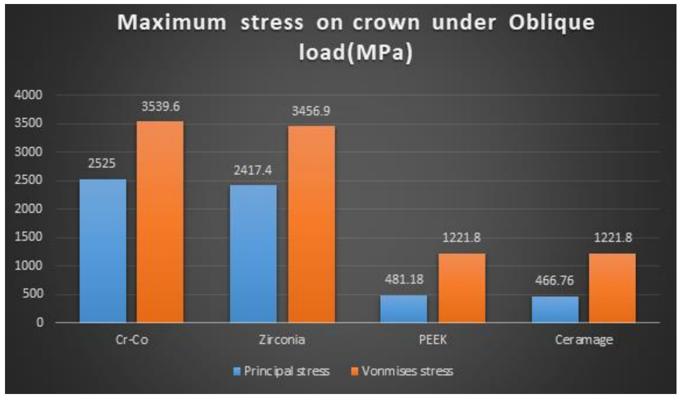
These stresses and displacements were interpreted by various colours. Red colour signifies the highest stress and dark blue colour the least stress. Finally, the results were processed and documented.

Results

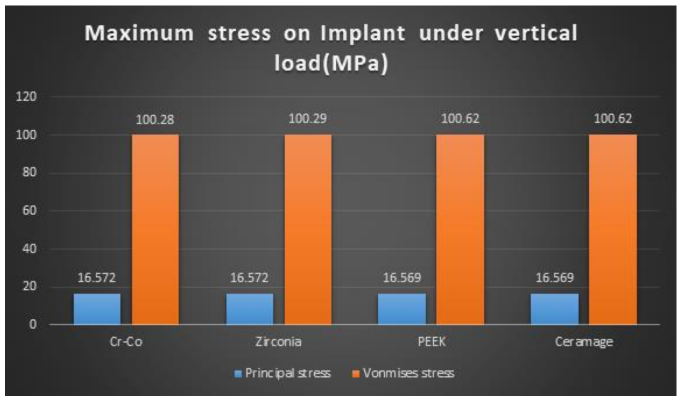
- Graph 1 represents the maximum stress on crown under vertical load of 200N. Maximum principal stress is observed in Zirconia (2169.3MPa) and least amount of stress observed in Ceram age (2040.2MPa)



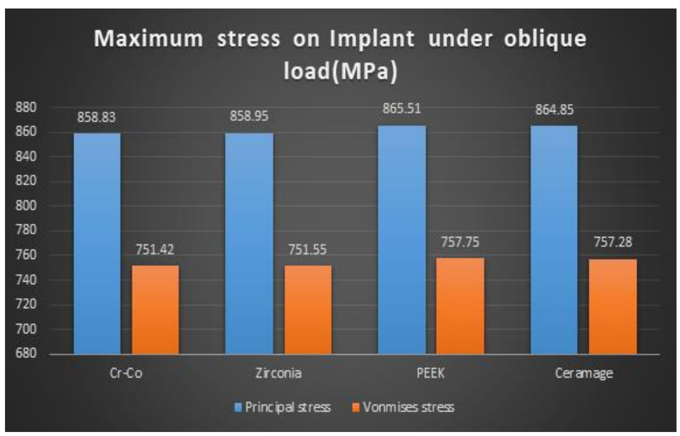
- Graph 2 represents maximum stress on crown under oblique load (100N). Principal stresses and Von-mises stresses are significantly higher for Cr-Co and Zirconia compared to PEEK and Ceram age. Maximum Principal stress is observed in Cr-Co (2525MPa) and least amount of stress observed in Ceram age (466.76MPa)



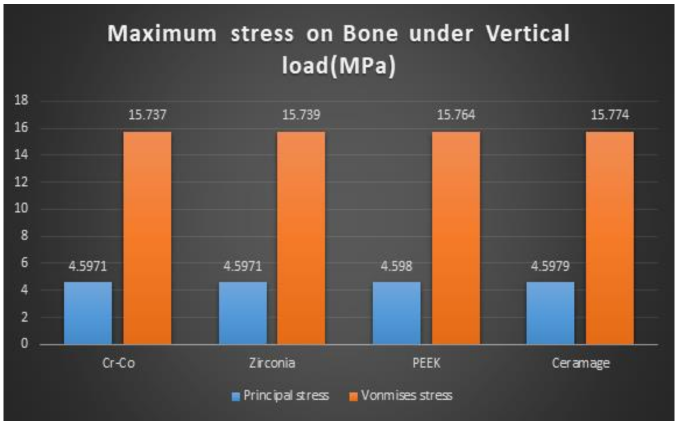
Graph 3: represents maximum stress on implant under vertical load (200 N).



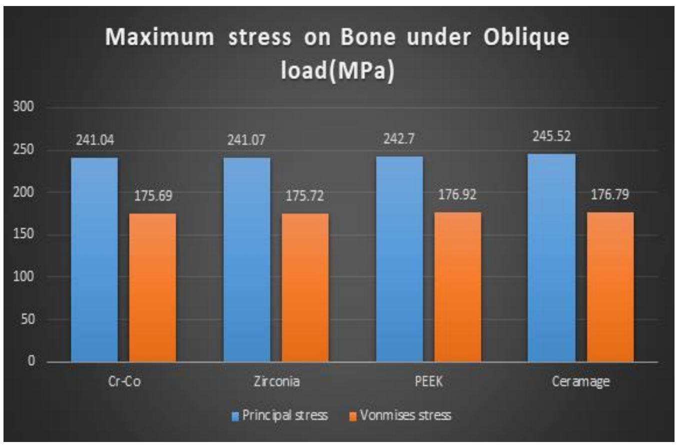
Graph 4: represents maximum stress on implant under oblique load (100 N).



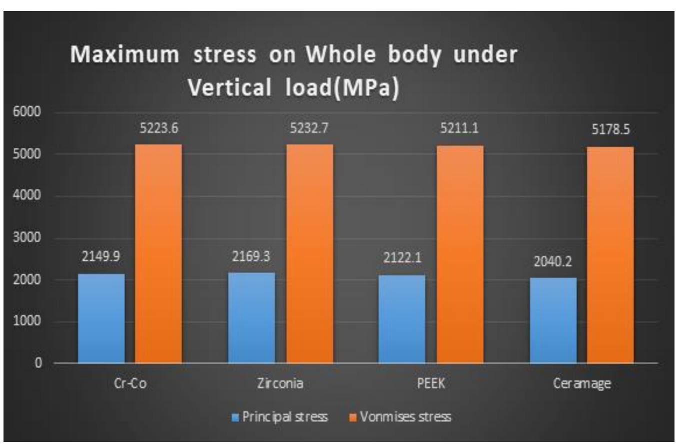
Graph 5: represents maximum stress on bone under vertical load



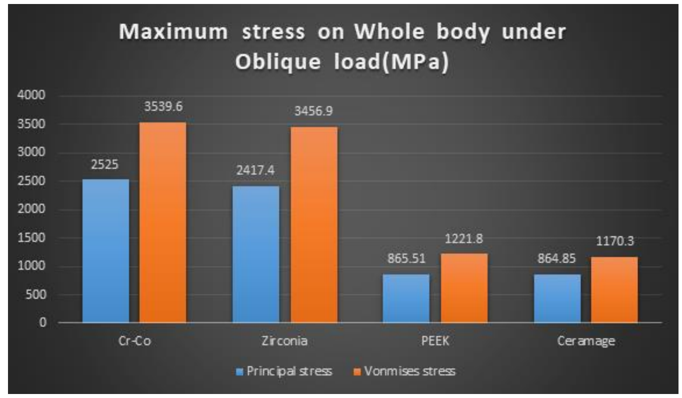
Graph 6: represents maximum stress on bone under oblique load.



Graph 7: represents maximum stress on whole body under vertical load.



Graph 8: represents maximum stress on whole body under oblique load.



Discussion

Teeth and Implants respond differently to masticatory forces, due to absence of periodontal ligaments, which serve as an elastic buffer(5,6). Analysing the biomechanics of this structures is challenging because of its complexity(55,56). The FEA,(55) is a suitable and analytic method of evaluating biomechanical behaviours in complex geometries by dividing the problem domain into a collection of much smaller and simpler domains (elements) in which the field variables can be interpolated with the use of shape functions.(13) In other words, FEA is a method whereby, instead of seeking a solution function for the entire domain, one formulates the solution functions for each finite element and combines them properly to obtain the solution to the whole body.(13) Moreover, 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 analyse biological or biocompatible structures produces more realistic results than 2D models.(57)

When applying FE analysis to dental implants, it is important to consider not only axial loads and horizontal force but also oblique force because the latter represents more realistic occlusal directions and, for a given force, will result in localized stress in cortical bone.(58) In the current study, both vertical and oblique loads were considered. The design of the occlusal surface of the model may influence the stress distribution pattern. In the current study, the locations for the force application were specifically described as the central fossa for axial load and buccal incline of the palatal cusp for oblique load. However, the geometric form of the tooth surface can produce a pattern of stress distribution that is specific for the modelled form. The pattern could be different with even moderate changes to the occlusal surface of the crown. The occlusal form used for this model would not be expected to be the same for all molar teeth.

In the present study, the intensities of vertical and oblique loads were not equal because the total vertical load, which was applied to the central fossa, was divided into buccal and palatal cusps, and the oblique load was directly applied to the palatal cusp.(59)

Moreover, oblique loads have been reported to increase stress values in peripheral bone and prosthetic components.(60)

Proper treatment planning and a sound understanding of restorative aspects of dental implants can prevent most implant failures.(61,62) Although the bone remodelling process is constantly dependent on the masticatory load (63), the overload (64) may cause damage to the alveolar bone, thereby promoting loss of osseointegration . The choice of a restorative material is an important decision because it could influence cases of excessive biting force or parafunctional habits. It could also prevent bone tissue from damage due to the fact that bone behaviour depends on load magnitude (63).

Available chromium-based alloys for casting single and multiple unit fixed restorations offer differing hardness and strength values. Most, however, are harder and stronger than their noble metal counterparts. Measured bond strengths of many base metal-porcelain combinations are comparable to those of noble alloy porcelain combinations.(65) Co-Cr alloys have high tensile strength (552 to 1034 Mpa) and high elastic modulus (200.000 Mpa). The high tensile strength permits use of thinner metal sections than would be possible if noble metal alloys were used. Co-Cr alloys have the highest elastic moduli of all dental alloys, which decreases flexibility to a significant degree. The flexibility of a fixed partial denture framework constructed of cobalt-chromium is less than half that of a framework of the same dimensions made from a high-gold alloy.(65) The Co-Cr alloy used in the present study was also used by Williams et al.(66) These authors investigated the effect of stresses on cantilevered prostheses attached to osseointegrated implants by FE analysis. The authors stated that Co-Cr alloy reduced the maximal and effective stresses. The much higher elastic modulus of Co-Cr allowed more uniform distribution of stress within the framework, providing more efficient and durable load transfer.

In the present study, a 4.3*10-mm dental implant was selected for its advantages including less surgical trauma, primary bone stabilization, postsurgical implant stabilization, and biocompatibility of the implant.(67) Understanding the effects of different designs in different bone qualities is important in implant selection and long-term success.(68,69)

In a 5-year analysis of Branemark implants, Jaffin and Berman17 reported that out of 949 implants placed in types 1, 2, and 3 bones, only 3% of the implants were lost, while out of 105 implants placed in type 4 bones, 35% failed. Bass and Triplett’s15 study correlating implant success with jaw anatomy for 1097 Branemark implants also revealed that bone quality 4 exhibited the greatest failure rate. Hutton et al16 likewise reported in a prospective study of 510 Branemark implants retaining overdentures that patients who possessed dental arches with bone quality 4 were at highest risk for implant failure

Several assumptions were made in the development of the model in the present study. The structures in the model were all assumed to be homogenous and isotropic and to possess linear elasticity. The properties of the materials modelled

in this study, particularly the living tissues, however, are different. For instance, it is well documented that the cortical bone of the mandible is transversely isotropic and in homogenous.(70) Cement thickness layer was also ignored.(71,72) All interfaces between the materials were assumed to be bonded or osseointegrated.(73–76) The stress distribution patterns simulated also may be different depending on the materials and properties assigned to each layer of the model and the model used in the experiments. These are inherent limitations of this study.(76)

Several studies have evaluated the effect of using different prosthesis materials on stress distribution in implants and peripheral bone structure and have reported that the change in prosthesis materials does not lead to major differences or has only a minor effect on the stress patterns.(29,29,77,78) Moreover, Bassit et al(79) supported these results in their in vivo study. Wang et al40 stated that the total energy transferred to the implant-bone interface was similar, although restorative crowns made of different materials might show different amounts of displacement. Similar biomechanical responses were observed in the present study. Although resin-matrix ceramics have been proposed as shock-absorbing materials,(80–82) a substantial decrease was not observed in the stress concentrations of implants and peripheral bone. Several layers or structures play a role in transmitting masticatory forces to implants and peripheral bone, including the restorative crown, cement layer, inner screw, and abutment.(77) The total energy transferred to the implant-bone interface first passes through the abutment-implant interface.(78) Some of the transmitted energy is considered to be absorbed by the intermediate structures. This may explain the similar biomechanical responses in implants with different superstructure materials.

Conclusion

Within the limitations of this study, the following conclusions were drawn;

1. Maximum Principal stress is observed in Cr-Co (2525MPa) and least amount of stress observed in Ceram age (466.76MPa) when oblique load of 100N applied on the crown
2. Von-mises stress observed maximum in Cr-Co (3539.6MPa) and least in PEEK (1221.8MPa) when oblique load of 100N applied on the crown
3. Maximum Principal stress is observed in Cr-Co (2525MPa) and least amount of stress observed in Ceram age (864.85MPa) whole bodily when 100N oblique load is applied.
4. Von-mises stress observed maximum in Cr-Co (3539.6MPa) and least in PEEK (1170.3MPa) whole bodily when 100N oblique load is applied.
5. In this study all four restorative materials are taking up the vertical load similarly, but when oblique load is applied there is a significant difference between maximum stresses taking up by each structure.
6. PEEK, Ceram age showed least amount of stress in crown and whole body when compared with Cr-Co and zirconia.

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