A 3-D Finite Element Analysis of Stress Distribution on Implant-supported Fixed Prosthesis with Four Different Commercially Available Implant Systems

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ABSTRACT

Aim: To investigate by the finite element analysis comparison of stress distribution on the cortical and cancellous bone in an implant-supported yttrium tetragonal zirconia polycrystals (Y-TZP FPD) in four different widely used implant systems under different loading conditions.

Materials and methods: Four 3-D finite element analysis (FEA) models of mandible having different implant systems with dimensions 8.0 mm × 5 mm in the second premolar and molar region were developed. In these models, abutment was tightened and 3-unit implant-supported Y-TZP FPD were cemented. A lateral force component of 100 N at 30° to the occlusal plane and a vertical intrusive force component of 250 N were applied to the central fossa of the FDP and the stress on bone around the implant was analyzed by FEA.

Results: In the four implant systems, the maximum stress values on the crestal bone differ for the different implant systems for the two loading conditions applied. In both cases, the maximum stress values on the cortical bone were in ADIN Touareg Closefit WP implants and the maximum stress on the cancellous bone was observed in the Nobel Speedy Groovy implants.

Conclusion: The ADIN Touareg Closefit WP implant system induced maximum stress on the crestal bone in both axial and buccolingual loading. Nobel Speedy Groovy implant system favored more equitable load distribution to the peri-implant crestal bone when compared to the other three implant systems.

Clinical significance: From this study, it was found that out of all the implants used for the study, the Nobel Speedy Groovy implant system favored more equitable load distribution due to the platform switch design contrary to the other systems and at the cancellous bone the least load was transferred by the Nobel Active implants due to the reverse buttress thread design and larger thread pitch.

Keywords: Abutment, Dental implants, Finite element analysis, Stress analysis.

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and root canals. Metal-free restorations are more popular compared to porcelain fused to metal (PFM) because of advances in material and fabrication technologies. The most recent metal-free material is yttrium-oxide partially stabilized (Y-TZP) zirconia. Y-TZP has superior mechanical properties like strength and high fracture resistance as compared to other metal-free systems. Oxide-containing ceramics have high biocompatibility, high abrasion resistance, improved color stability, and aesthetics. However, the comparison of stress distribution on the bone with different implant systems under different loading conditions has not been sufficiently assessed. Therefore, the purpose of this study was to compare stress distribution on the cortical and cancellous bone in a three-unit implant-supported yttrium tetragonal zirconia polycrystals (Y-TZP FPD) in four different widely used implant systems under different loading conditions by using FEA.

**Materials and Methods**

In the present *in vitro* study, four geometric models were created using computer-aided three-dimensional interactive application (CATIA) program (version 12) and then converted into 3-D FEMs by using the Hypermesh software 7.0 to represent an edentulous human mandible having four different commercially available implants. The model included mucosa, teeth with dentine, and periodontium. Two implants were placed over the second premolar to second molar region supported by the yttrium oxide partially stabilized tetragonal zirconia polycrystalline fixed partial denture. The models were then subjected to a 250 N vertical intrusive load and lateral load of 100 N at an angle of 30° representing the masticatory force applied to the fixed dental prosthesis. The ANSYS (analysis system) software (version 12) was used to evaluate the resultant von Mises stress induced on the crestal bone.

**Model Designing**

**Modeling of Mandible**

The geometric model of half of the mandible consisting from the central incisor to the second molar region, with missing second premolar, first and second molar, was developed using computed tomography (CT) scan (SIEMENS, DICOM, Syngo CT2006 C2 format) of a patient having cross-sections of 0.25 mm for improved resolution. Total 218 sections of 640 × 640 voxels each were taken. The DICOM data were then converted into the geometric model using the MIMICS software. This data were exported to RAPIDFORM (Geomagic, Asia Pacific) in the STL format to create the surface data. The surface data are converted to the IGES format using HYPERMESH. In HYPERMESH, the individual parts like enamel, cementum, compact bone, and periodontal ligaments (PDL) were then discretized and assembled.

**Development of Various Components of the Model**

Each component was designed separately and then assembled. The mandibular residual ridge of each model was represented by moderate resorption. The mandibular model consisted of three layers, the mucosa, the underlying cortical bone, and cancellous bone. This residual ridge supported the implants with the overlying attachments and the prosthesis. Two titanium implants from four major implant systems, i.e., ADIN Swell implants (Fig. 1A), Nobel Biocare—Nobel Active implants (Fig. 1B), ADIN—Touareg Closefit WP (Fig. 1C), Nobel Biocare—Nobel Speedy Groovy implants (Fig. 1D), implants having length and diameter of 8 mm and 5 mm, respectively, were modeled in the second premolar and second molar positions in the mandible. Abutments were modeled and fixed to the fixture with 25 N cm torque. A three-unit framework Y-TZP was modeled according to the manufacturer's instruction. The Y-TZP fixed partial denture was cemented to the abutments with a dual-cure resin cement (RelyX ARC, 3M ESPE AG, Seefeld, Germany) having 0.025 mm thickness.

**Creation of FEM model**

The creation of FEM was the next step. This is known as the meshing of the model and was done with the computer program—Hypermesh 7.0—in which the model was subdivided into elements whose apexes meet to form nodes. These elements remained in contact irrespective of the size and nature of stresses generated in a computer simulation.

All the materials used in the study were assumed to be homogeneous, linearly elastic, and isotropic. The material properties of the dentures, mucosa, cortical bone, cancellous bone,
implants, and attachments are then incorporated. All conditions are set and the analysis was done using the ANSYS software, version 12. The material properties are tabulated in Table 1.

**Loading**

A functional force analogous to occlusal loading of 250 N was applied vertically and a 30° lateral buccolingual force of 100 N was projected at the central fossa of the three-unit FDP (center of mastication) and the stress patterns produced under such loading within the models were measured.

**Stress Analysis**

Following loading, the maximum von Mises stress at the implant–bone interface and along the different layers in all the models was assessed using the finite element program (ANSYS software, version 12).

**Observations and Results**

The present study was performed to evaluate and compare the stresses on a three-unit implant-supported fixed prosthesis with four different commercially available implant systems. A total of four implant models of the mandible with three-unit fixed partial dentures cemented on them were designed. All the models, i.e., ADIN Swell implants (Fig. 2), ADIN Touareg Closefit WP (Fig. 3), Nobel Active (Fig. 4), and Nobel Speedy Groovy (Fig. 5), were subjected to a lateral force component of 100 N at an angle of 30° and a vertical intrusive component of 250 N parallel to long axis of the implant-supported FDP. Loading stresses were induced at the implant–bone interface on both the cancellous and the cortical bones. These stress color plots obtained were evaluated and the maximum von Mises stress induced at the implant–bone interface was compared and tabulated. Table 2 and Figure 6 describe the evaluation and comparison of stresses on cortical bone with implant systems under axial and buccolingual loading conditions. Table 3 and Figure 7 describe the evaluation and comparison of stresses on cancellous bone with implant systems under axial and buccolingual loading conditions.

**Discussion**

Several implant concepts have been developed but bone loss and implant failure still remained concerns to the clinicians and the patients. Functional loading creates strain, resulting in bone remodeling around implants. Therefore, long-term survival of dental implants depends on proper biomechanical considerations. For this, stress analysis of the bone implant and mechanical interactions are important. To investigate stress distribution around the peri-implant bone, various methods have been currently explored. In this study, a 3-D FEA was conducted to find the stresses in four widely used implants systems and comparing the stresses they impart on the surrounding bone. Most FEA models show a state of complete osseointegration, which usually does not occur so exactly in clinical situations. The aim was to compare, by means of three-dimensional finite element simulations, load transmission on four commercially available osseointegrated implants in functioning conditions. Two types of loads were projected to the Y-TZP framework. All the materials were considered to be hemogenous and isotropic, which is the limitation of the study. When applying FEA to the prosthesis, we should consider not only axial loads but horizontal and combined loads too. This physiological occlusal loading will result in localized stress at cervical area and at the implant neck.

![Table 1: Material characteristics used in the study](image)

| Material     | Young’s modulus (N/m²) | Poisson’s ratio |
|--------------|------------------------|----------------|
| Cortical bone| 1.37 × 10⁴              | 0.26           |
| Tooth        | 1.96 × 10⁴              | 0.30           |
| PDL          | 0.667 × 10³             | 0.45           |
| Y-TZP        | 2.1 × 10⁵               | 0.23           |
| Titanium     | 1.13 × 10⁵              | 0.33           |

Figs 2A to D: ADIN Swell implants: (A) von Mises stresses on the cortical bone under axial loading (buccal view); (B) Stresses on the cortical bone under lateral loading (buccal view); (C) Stresses on the cortical bone under axial loading (lingual view); (D) Stresses induced at the cancellous bone under axial loading.
The nodal points of load application were on the buccal side of the framework in both types of loading conditions.

The results revealed that maximum stress values differ for the different implant systems under both types of loads (100 N and 250 N), because constraints and geometry were different for different analyzes. The structure response was the same, even though maximum stress values varied. The maximum stress values on the cortical bone under the same loading conditions were on ADIN Touareg Closefit WP, i.e., 40.1 MPa, followed by Nobel Active implants, i.e., 38.8 MPa, ADIN Swell, i.e., 36 MPa, and the least for Nobel Speedy Groovy, i.e., 32 MPa. A common finding from all the models was that maximum stress concentration at the bone–implant interface was at the level of the neck of implant. This is in agreement with the findings of Hoshaw et al.14 Bozkaya15 found overloading occurred near the superior region of the compact bone and concluded that the crestal module may play a role in minimizing stresses to bone. On the contrary to the study conducted by Bozkaya,15 the crest module of the ADIN Touareg Closefit WP implant system had a narrower crest module than the outer thread diameter and all the other three implant systems had a larger crest module. This led to the increased stresses on the compact bone, which ultimately will lead to more of the crestal bone resorption. These results are tabulated in Table 2.

The stress values in the cortical bone were more than the cancellous bone as the remodeling of bone occurs throughout the life result in changing its mechanical behaviour. Osteons in the cortical bone are aligned parallel to the bone’s long axis or

Figs 3A to D: ADIN Touareg Closefit WP: (A) von Mises stresses induced at the cortical bone under axial loading (buccal view); (B) Stresses on the cortical bone in lateral loading (buccal view); (C) Stresses on the cortical bone under axial loading (lingual view); (D) Stresses induced at the cancellous bone under axial loading

Figs 4A to D: Nobel Active implants: (A) von Mises stresses induced at the cortical bone under axial loading (buccal view); (B) Stresses on the cortical bone under lateral loading (buccal view); (C) Stresses on the cortical bone under axial loading (lingual view); (D) Stresses induced at the cancellous bone under axial loading
in case of short bones along the direction of forces; so, it resists more deformation to higher loads than does the cancellous bone. The maximum equivalent stress in the cancellous bone was shown near the apical region of the four implant system, out of which the maximum stresses were observed in the Nobel Speedy Groovy implants, i.e., 5.14 MPa in the axial loading and 2.1 MPa in the buccolingual loading, which were considerably lower than those shown in the cortical bone. This might be due to the stress-transferring mechanism that occurred in the implant-bone complex. The stresses resulting from the occlusal loads are immediately transferred to the cervical cortical bone, but much lower stress spread to the cancellous bone at the apical region.

Thread pitch is the distance between adjacent threads of an implant. Distance between the center of two adjacent threads, measured parallel to the axis of an implant, is defined as thread pitch. Smaller the pitch, more threads on the implant body, thus the greater surface area per unit length of the implant body if all other factors are equal. The designs of the threads in dental implants include square, V-shaped, buttress, and reverse buttress. The square or power thread transmits better compressive loads due to more surface area. At the cancellous bone, maximum von Mises stress was seen at V-thread design, i.e., for the Nobel Speedy Groovy implants. Least von Mises stress at bone is with the reverse buttress thread, i.e., for the Nobel Active implants. This is in agreement with the findings of Oswal et al. who conducted a study on influence of three different implant thread designs on stress distribution.

The present study has certain limitations; first, all the vital tissues that are anisotropic were considered isotropic. The loads applied were static but there are always dynamic loads during function. Even though FEA provides a sound theoretical basis, it should not be considered alone for predicting the response of biological systems to applied loads. Actual experimental techniques and clinical trials should follow FEA to establish the influence of observed stress levels on the tissue and prosthesis function.  

**Summary and Conclusion**

Within the limitations of the present FEA study, the following conclusions were drawn: the ADIN Touareg Closefit WP implant system induced maximum stress on the crestal bone in both axial and buccolingual loading. The Nobel Speedy Groovy implant system induced least stress on the crestal bone. Maximum stresses were observed on the cancellous bone on both the axial and
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buccolingual loading by the Nobel Speedy Groovy implant system. Minimum stresses were observed on the cancellous bone on both the axial and buccolingual loading by the ADIN Touareg Closefit WP implant system. Considering the results obtained, it can be inferred that the Nobel Speedy Groovy implant system favored more equitable load distribution to the peri-implant crestal bone when compared to the other three implant systems. This system had the most favorable crest module and dissipated less amount of stress on the cortical bone.

C L I N I C A L  S I G N I F I C A N C E

From the present study, it can be concluded that out of all the implants used for the study, the Nobel Speedy Groovy implant system favored more equitable load distribution due to the platform switch design contrary to the other systems and at the cancellous bone the least load was transferred by the Nobel Active implants due to the reverse buttress thread design and larger thread pitch.

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Table 3: Evaluation and comparison of stresses on cancellous bone with implant systems under different loading conditions

| Implant system       | Maximum stress (MPa) | Maximum stress (MPa) |
|----------------------|----------------------|----------------------|
|                      | Axial loading        | Buccolingual loading |
| ADIN Swell           | 4.7                  | 2                    |
| Nobel Speedy Groovy  | 5.14                 | 2.1                  |
| Nobel Active         | 4.46                 | 1.98                 |
| ADIN Touareg Closefit WP | 3.95             | 2                    |

Fig. 7: Evaluation and comparison of stresses on cancellous bone with implant systems under different loading conditions