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Impact of short implants numbers and prosthesis design on stress in the posterior mandible: FE analysis

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ABSTRACT

Background: This study assessed the effect of the number of short implants on stress and strain distribution in bone in the posterior mandible using finite element analysis (FEA).

Materials and Methods: The study design utilized FEA, a computational technique. In FEA models, short implants (4 mm diameter and 6 mm length) were placed at the site of the mandibular first premolar to the second molar in four models: (I) two implants at the sites of teeth #4 and #7 with two pontics at the sites of teeth #5 and #6, (II) three implants at #4, #5, and #7 with one pontic at #6, (III) three implants at #4, #6, and #7 with one pontic at #5, and (IV) four implants at #4, #5, #6, and #7 with no pontic. A 100 N load was applied vertically and at a 30° angle to the occlusal surface of the crowns. Stress and strain distribution patterns in bone were evaluated using ANSYS Workbench.

Results: The highest maximum von Mises and shear stress and strain values under vertical and off-axial loadings were observed in the model with two short implants at the sites of teeth #4 and #7 with two pontics at the sites of teeth #5 and #6. In general, the highest stress and strain values were recorded following the application of off-axial loads compared to vertical loads. In all models, the highest stress was noted in the cervical part of the implants, while the maximum strain occurred in the apical part of the implants.

Conclusion: Increasing the number of short implants significantly reduces stress and strain values in peri-implant bone.

Key Words: Dental implants, finite element analysis, strain, stress

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INTRODUCTION

The use of endosseous dental implants to replace missing or hopeless teeth has become routine clinical practice over the past three decades. Implant-supported fixed prostheses are often considered the treatment of the first choice. Clinical success largely depends on the biomechanical behavior of implants in terms of stress and strain transfer to supporting bone. Long implants were initially preferred, despite early finite element analyses indicating that major stress transfer to surrounding bone is primarily limited to the first 3–5 threads.[1] However, in the posterior mandible, alveolar bone resorption may limit the use of long

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implants (>8 mm)[2,3] due to the proximity of the mandibular neurovascular bundle.[4,5] A minimum of 2 mm of bone height should remain undisturbed above this vital structure to avoid nerve damage.[6,7] Avoiding the mental nerve is also a consideration at mandibular bicuspid sites.[8,9] In additional, lingual mandibular bone concavities may increase the risks of fenestrations or perforations of the lingual cortical plate.[10] Short (6–8 mm) or even ultrashort (<6 mm) implants often allow effective treatment.

Short-threaded implants had a mixed history in the past,[11] but substantial evidence now supports their use with proper technique and implant design.[12] Most implant manufacturers now offer short implants for use in the posterior mandible.

Current short implant designs feature moderately rough surface textures to increase surface contact with bone.[13] Due to the high crown/implant ratios associated with short/ultra-short implants, prosthesis design should ensure favorable occlusal load distribution.[14] Splinting short implants helps distribute occlusal stresses among connected implants,[12] and increasing the number of short implants in a splinted prosthesis further aids stress distribution per unit area.[15] Tabrizi *et al*.[15] reported that increasing the number of short implants in splinted prostheses reduces marginal bone loss.

A noninvasive way to predict *in vivo* stress distribution with dental implants is through computerized modeling.[16] Finite element analysis (FEA) is widely regarded as a suitable method for predicting three-dimensional (3D) stress and strain patterns around dental implants.[17,18] However, 3D FEA studies on optimal load distribution with implant-supported fixed prostheses in the posterior mandible are limited. This study aimed to assess the effect of the number of short, splinted implants, and prosthesis designs on load distribution.

MATERIALS AND METHODS

This study employed FEA, a computational technique in biomechanics for analyzing hard tissue modeling. Ethical approval was obtained from the Ethical Committee, with the approval code IR.IAU.KHUISF.REC.1398.27. A 3D finite element model was developed to calculate the maximum von Mises stress, shear stress, von Mises strain, and shear strain values around splinted short implants placed in the posterior mandible. Implants (SIC invent AG, Basel, Switzerland) measured 6 mm in length and 4 mm in diameter (abutment platform: 4 mm). Loads of 100 N were applied vertically and obliquely (30°).

Modeling and three-dimensional scanning

Four models with eight geometric configurations and two loading conditions were simulated in the posterior mandible. Combinations of sites for the first (#4) and second (#5) premolars and the first (#6) and second (#7) molars were as follows:

(Ia) Four implants (sites #4, #5, #6, and #7) loaded with 100 N applied vertically. (Ib) Four implants (sites #4, #5, #6, and #7) loaded with 100 N applied at a 30° angle. (IIa) Three implants (sites #4, #5, and #7) with a pontic at site #6, loaded with 100 N applied vertically. (IIb) Three implants (sites #4, #5, and #7) with a pontic at site #6, loaded with 100 N applied at a 30° angle. (IIIa) Three implants (sites #4, #6, and #7) with a pontic at site #5, loaded with 100 N applied vertically. (IIIb) Three implants (sites #4, #6, and #7) with a pontic at site #5, loaded with 100 N applied at a 30° angle. (IVa) Two implants (sites #4 and #7) with two pontics at sites #5 and #6, loaded with 100 N applied vertically. (IVb) Two implants (sites #4 and #7) with two pontics at sites #5 and #6, loaded with 100 N applied at a 30° angle.

An ATOS II (GOM GmbH, Braunschweig, Germany) scanner with ATOS Viewer v6.30 was used for 3D scanning. CATIA software (version R21, Dassault Systèmes, France) was used for 3D modeling. ANSYS software (version16.1, Dassault Systèmes, France) was employed for FEA.

Table 1 shows the behavioral properties of the materials used. ANSYS meshing employed smaller elements in critical areas for more accurate results. Tetrahedral elements were used for meshing all components, and hexahedral elements were used for the bar. All elements were quadratic with high precision.

Table 2 presents the element data. Models were subjected to 100 N vertical and off-axial loads at a

Table 1: Behavioral properties of the materials used

Material	Modulus of elasticity (MPa)	Poisson's ratio
Cortical	13,400	0.3
Porcelain	68,900	0.28
Cancellous bone	1370	0.3
Titanium	110,000	0.35

30° angle. Compressive loads were applied to the occlusal surface of the porcelain. To prevent jaw movement, its inferior border was fixed. Symmetry allowed only half of the jaw to be modeled. At the sectioned site, frictionless boundary conditions were applied. Contact between components was linearly bonded, allowing no sliding or separation.

Critical points in cortical and cancellous bone were selected for measurement and located at implant threads in the coronal (cortical bone) and apical (cancellous bone) regions [Figure 1]. Equivalent (von Mises) stress, shear stress, and strain values were calculated at these points. Each implant yielded 16 data points.

RESULTS

Table 3 shows the highest and lowest stress and strain values in all eight FEA models. The highest stress and strain values under vertical and off-axial loadings were observed in the model with two short implants and two pontics. Conversely, the lowest values were noted in the model with four splinted short implants.

Models II and III showed reduced stress and strain values and more homogeneous distribution patterns in models with three implants at sites #4, #6, and #7 with a pontic at the second premolar site compared to three implants at sites #4, #5, and #7 with a pontic at the first molar site. Off-axial loads generally resulted in higher stress and strain values than vertical loads. Maximum stresses were noted in the implant neck regions, while maximum strains occurred apically. Cortical bone recorded the highest stress values, and trabecular bone recorded the highest strain values.

Table 2: Element data

Variable	Data
Number of elements	2,227,491
Number of nodes	3,380,796
Type of elements	Tetrahedral + hexahedral
Element order	Quadratic
Size of elements for the bar	0.25 mm
Size of elements for the porcelain	0.5 mm
Size of elements for the fixture and abutment	0.25 mm
Size of elements for cortical bone	0.5 mm
Size of elements for cancellous bone	0.5 mm
Size of elements for the external surface of fixture	0.1 mm
Size of elements for the internal surface of cortical bone and cancellous bone	0.1 mm

DISCUSSION

This study evaluated the effects of the number of short implants on stress and strain distribution in the posterior mandible using 3D FEA. Bone constantly remodels in response to mechanical loads, preserving its mechanical properties.[19] Stress induces strain, causing deformation. A strain of 1,000 $\mu\varepsilon$ equates to a 1% change in bone length. Excessive strain can lead to fatigue fractures, while insufficient strain may result in bone resorption ("disuse atrophy").[19,20] Repetitive stresses exceeding 3000 $\mu\varepsilon$ can cause microdamage and marginal bone loss, adversely affecting osseointegration.[21]

Bone has a porous structure with complex and tiny micro-structures. It is anisotropic and different parts have different physical properties.[22] Around dental implants stress transfer from occlusion occurs at the bone-to-implant interface in cortical bone primarily at the most coronal implant threads. Strain is highest here because cortical bone has a lower modulus of elasticity than cancellous bone.[23]

Unless certain precautions are taken,[22-26]

Marginal/crestal bone loss may occur post-implant placement to re-establish biological width,[27] but significant further loss is not anticipated with proper hygiene and absence of risk factors.[28]

In vitro studies suggest that excessive biomechanical stresses due to incorrect occlusal design,[29] or framework misfit[30] of the implant-supported restoration can adversely affect stability of marginal bone. Since too much stress can lead to unwanted MBL, choosing the appropriate number of implants to restore an edentulous space is crucial. Excessive

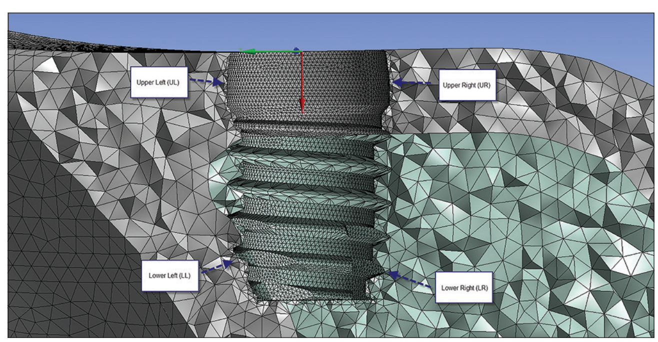

Figure 1: Four points of measurement in section of the first coordinate system model (2 upper in cortical bone and 2 lower in cancellous bone). UK: Upper left, UP: Upper right, LL: Lower left, LR: Lower right. Image Properties: Extension: jpg; Width: 5056; Height: 2554; Resolution: 300/300.

Table 3: Highest and lowest values of stress and strain in all eight finite element analysis models

	Highest maximum von Mises stress	Lowest maximum von Mises stress	Highest maximum shear stress	Lowest maximum shear stress	Highest maximum von Mises strain	Lowest maximum von Mises strain	Highest maximum shear strain	Lowest maximum shear strain
Ia VL	1.9055 MPa (implant 7) Cortical	0.1354 MPa (implant 4) Cancellous	1.0801 MPa (implant 7) Cortical	0.0778 MPa (implant 4) Cancellous	713 με (implant 6) Cancellous	53 με (implant 4) Cortical	1010 με (implant 6) Cancellous	77 με (implant 4) Cortical
Ib OL	4.2742 MPa (implant 6) Cortical	0.7066 MPa (implant 4) Cancellous	2.4465 MPa (implant 6) Cortical	0.4041 MPa (implant 4) Cancellous	1140 με (implant 6) Cancellous	48 με (implant 5) Cortical	1640 (implant 6) Cancellous	69 με (implant 5) Cortical
IIa VL	3.1487 MPa (implant 7) Cortical	0.5706 MPa (implant 4) Cancellous	1.7718 MPa (implant 7) Cortical	0.328 1 Mpa (implant 4) Cancellous	890 με (implant 7) Cancellous	52 με (implant 4) Cortical	1292 με (implant 7) Cancellous	74 με (implant 4) Cortical
IIb OL	5.5191 MPa (implant 5) Cortical	0.29102 MPa (implant 4) Cancellous	3.1678 MPa (implant 5) Cortical	0.15666 MPa (implant 4) Cancellous	1150 με (implant 5) Cancellous	67 με (implant 5) Cortical	1680 με (implant 5) Cancellous	99 με (implant 5) Cortical
IIIa VL	2.45 MPa (implant 6) Cortical	0.10 MPa (implant 7) Cancellous	1.38 MPa (implant 6) Cortical	0.057 MPa (implant 7) Cancellous	834 με (implant 4) Cancellous	75 με (implant 7) Cancellous	1140 με (implant 4) Cancellous	109 με (implant 7) Cancellous
IIIb OL	2.96 MPa (implant 7) Cortical	0.0897 MPa (implant 6) Cancellous	1.71 MPa (implant 7) Cortical	0.051 MPa (implant 6) Cancellous	1690 με (implant 6) Cancellous	71 με (implant 6) Cortical or cancellous	2450 με (implant 6) Cancellous	98 με (implant 6) Cortical or cancellous
IVa VL	4.8167 MPa (implant 7) Cortical	0.6328 MPa (implant 7) Cancellous	2.6885 MPa (implant 7) Cortical	0.36513 MPa (implant 7) Cancellous	1213 με (implant 7) Cancellous	83 με (implant 4) Cortical	1779 με (implant 7) Cancellous	124 με (implant 4) Cortical
IVb OL	7.9679 MPa (implant 4) Cortical	0.4084 MPa (implant 7) Cancellous	4.5929 MPa (implant 4) Cortical	0.2339 MPa (implant 7) Cancellous	1847 με (implant 4) Cancellous	266 με (implant 7) Cortical	2687 με (implant 4) Cancellous	381 με (implant 7) Cortical

VL: Vertical loading; OL: Off-axial loading

MBL may lead to microbial infection of exposed implant surfaces leading to inflammation-induced bone resorption and peri-implantitis.

Waskewicz *et al*.[31] reported that peri-implant stress generation begins following prosthesis placement, and can be decreased with appropriate prosthesis design.[29-31]

FEA is a valuable tool for studying stress distribution in implant-supported prostheses.[32-34] In this study, vertical and off-axial loads were applied to assess the impact of implant number on load distribution. Results indicated that increasing implant numbers in the posterior mandible reduces stress and strain values, aligning with Tabrizi *et al*.[15] and Gümrükçü and Korkmaz's findings.[35] The optimal configuration for restoring posterior mandibular sites with short implants appears to be three implants with one pontic at the second premolar site.

CONCLUSION

Increasing the number of splinted short implants in the posterior mandible decreases stress and strain values under both vertical and off-axial loads. Maximum stress was observed in cortical bone, whereas maximum strain was recorded in trabecular bone. The configuration of three implants at sites #4, #6, and #7 with one pontic at the second premolar site provided the most uniform stress and strain distribution.

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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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