Original Article

Effect of Abutment Height Difference on Stress Distribution in Mandibular Overdentures: A Three-Dimensional Finite Element Analysis

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Abstract

Background and Aim: Implant-supported overdentures are a treatment option for edentulous patients. One of the important factors in determining the prognosis of overdenture treatment is to control the distribution of stress in the implant-bone and attachment complex. This study assessed the effect of implant abutment height difference on stress distribution in mandibular overdentures.

Materials and Methods: In this study, three models of mandibular overdentures were designed independently using finite element analysis (FEA). The implants were placed at different height levels relative to the adjacent implant (1 mm, 2 mm and 3 mm). A 100 N load was applied to the overdenture, and the software was programmed for stress analysis in the models. The load was applied bilaterally, unilaterally, vertically, and obliquely. Finally, the von Misses stresses were produced numerically, color-coded, and compared among the models.

Results: The models in which the implants had up to 2 mm height difference with each other showed better stress distribution than the model with 3 mm height difference between the implants. In all conditions, the implant neck showed the highest concentration of stress among all areas of the implant. Lower stress levels were found in the cancellous bone than the cortical bone in different loading conditions.

Conclusion: Lower Von Mises stress values were found in the models with up to 2 mm difference in implant height, and higher stress values were noted in the cortical bone and the implant neck compared with trabecular bone.

Key Words: Finite Element Analysis; Alveolar Bone Loss, Dental Abutments; Denture, Overlay

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Introduction

Patients with severe ridge resorption have numerous problems associated with complete dentures, such as poor support, retention and stability. [1] It is even difficult for an individual to have routine daily activities with these types of prostheses. [2] Therefore, implant-supported overdentures are considered as an alternative treatment to improve the retention, support and stability of prostheses, as well as patient satisfaction and nutritional status. [1, 3]

Implant-supported overdentures are simple and non-invasive treatments with high clinical success rate and reasonable cost. [4, 5] To enhance the prognosis of this treatment, functional forces must be properly distributed in bone, mucosa and attachments. The goal of treatment should be minimizing the mechanical stress on dental implants and the adjacent alveolar bone. [6]

Various attachments are available in implant-supported overdentures, such as bar, locator, and ball and magnet attachments. Stud attachments are the most common type which are also very easy to use. [7, 8] There is no consensus on the superiority of any of the attachment systems. 9-12] Ball attachments are used in implant-supported overdentures due to their simplicity and cost-effectiveness. [13] These attachments have adequate retention, can absorb the stress, compensate the implant's disparallelism and reduce the functional loads applied to the implants. [14] Patients can insert or remove their overdentures conviniently with ball attachments. [15]

The amount of alveolar bone resorption can be different in various sites of the mandible, which affects the distribution of stress in the implant-attachment system.[2, 16] Clinicians mention that inserting the implants at the same level improves stress distribution. If one implant is placed higher than the other, cortical bone loss may increase adjacent to the higher implant. [2]

Stress distribution in tooth structure can be evaluated using methods such as mechanical stress analysis, strain measurements, and photo-elastic analysis. Finite element analysis (FEA) is another method which has numerous advantages such as accurate modeling of complex structures, modifying the models, and displaying internal stresses in different loading conditions. [17, 18]

Most of the studies using FEA compared stress generation between implants placed in the same occlusal level [1, 10, 18] and few studies [2, 16] evaluated stress distribution in implants with different positions in term of height. Therefore, the aim of this study was to determine the effect of abutment height difference on stress distribution in mandibular overdentures.

Materials and Methods

A)Designing the models

A cone-beam computed tomography image of an edentulous mandible was imported to Mimics Medical 21.0 [1] (Materialise Interactive Medical Image Control System; Materialise, Leuven, Belgium) to generate a three-dimensional surface model. The model was modified and the extracted file was imported to CATIA V5 [1] (Computer Aided 3D Interactive Application) software (Figure 1).

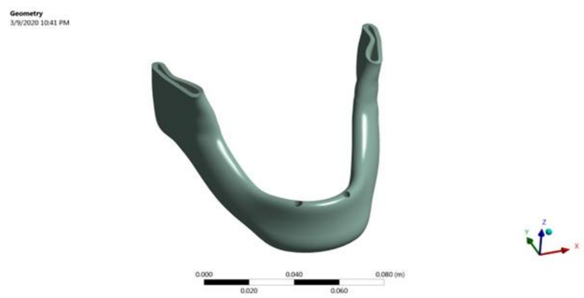

Figure1. 3D model of the mandible

The implants, ball attachments, and a mandibular overdenture were scanned and imported to CATIA V5 software (Figure 2). The buccolingual width of the alveolar crest was 6 mm with 2 mm cortical bone, and implants (4.0 × 11.5 mm; DIO Implant System, Korea) were placed 23 mm apart from each other. Three groups of models were created, and in each model the left implant was placed lower in the alveolar bone at different heights compared with the right implant (model 1: 1 mm difference between the implant levels, model 2: 2 mm difference between the implant levels, model 3: 3 mm difference between the implant levels).

B) Meshing

In this phase, the volumes designed in the model (overdentures, attachments and alveolar

Figure2. Complete model of the mandible and the overdenture.

bone) were divided into several elements which contained the material characteristics of the desired area (according to the information entered in the software). By using ANSYS 15.0 workbench software, [1] the working models were converted to mesh models. To generate the meshes, 10-node tetrahedral elements were employed. Mesh refinement was done, and stress variation was minimized to less than 1%. The number of nodes and elements used in the models is presented in Table 1.

C) Material properties, boundary conditions and contact elements

Table 1. Number of nodes and elements

Models	Model 1	Model 2	Model 3
Number of nodes	237377	308352	242397
Number of elements	158585	205018	162214

In the next step, the mechanical properties of the materials (cortical bone, cancellous bone, acrylic overdenture, implants and attachments) were recorded in the software according to the available literature. [1, 2, 16, 19] All the structures and materials were considered to be linearly elastic, isotopic and homogeneous. At the uppermost area of the models, node removal was restricted as the boundary condition. The contact between the overdenture and the underlying tissues was considered to be frictionless. The bone-implant interface was assumed to be continuous with complete osseointegration so the boundary conditions were set as fixed between the implant and bone. The inner surface of the overdenture was adapted to both implant heights. The mechanical properties of the materials in the models are shown in Table 2.

D) Loading conditions

The load was applied bilaterally and perpendicular to the center of the first molar, unilaterally (on the first molar), vertically, and obliquely (with 30-degree angle) on the left side and perpendicular to the midline. The load values were 100 N in unilateral and 50 N (each side) in bilateral conditions. Finally, the software was programmed to analyze the stress distribution in bone-implant-attachment system in different loading conditions. To indicate the Von Mises stress values, a color map was plotted. Red color was used for the parts with the highest stress values and dark blue color showed the parts with the lowest stress values.

Results

The models with up to 2 mm abutment height difference (models 1 and 2) revelead better stress distribution in bilateral and unilateral loading conditions compared with model 3.
(Figures 3 and 4). The Von mises stress value in the upper part of the left implant by applying a vertical load (100 N) from the left side was 2.5 MPa in model 1, which was found to be approximately 2 times lower than the stress value in the upper part of the lower implant in model 3 (5.05 MPa). The stress value in the upper part of the left implant in model 1 by applying a vertical load (100 N) in the front rigion was 8.5 MPa, which was approximately 1.3 times lower than the stress value in the upper part of the left implant in model 3 (10.8 MPa). In model 3, the stress value in the upper part of the lower implant was 0.71 MPa by applying a bilateral load (simultaneously on the right and left sides).
However, in model 1 with the same loading condition, the stress value in the upper part of the lower implant was 0.33 MPa which was approximately 2.15 times lower (Table 3). The amount of stress values in the right implant are shown in Table 4.
In all models, the Von mises stress values were greater in the implant neck in comparison with the middle part and the apex of the implant.

Table 2. Mechanical properties of the materials in the model

Materials	Poisson's ratio	Young's modulus (MPa)	References
Cortical Bone	0.3	13700	1, 2, 16, 19
Trabecular Bone	0.3	1370	1, 16, 19
Nylon rubber	0.3	5	1
Acrylic Resin	0.3	3000	1, 2, 16
Stainless steel	0.3	190000	1
Ti6Al4V	0.3	134000	1
Titanium grade 4	0.3	114000	1, 19

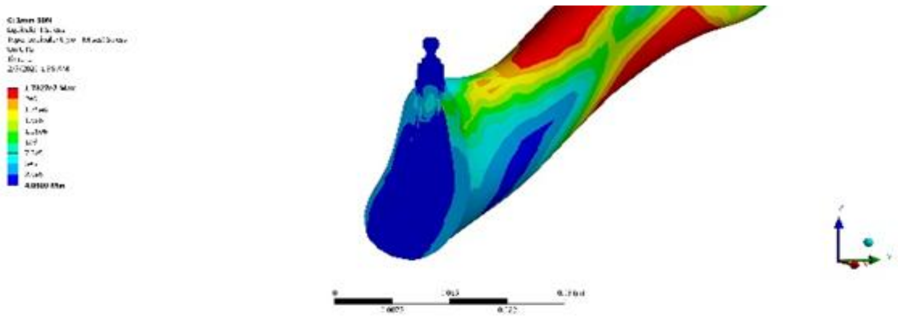

Figure 3. The stress distribution in the implant – attachment – bone system under bilateral vertical loading (1mm height differences between the implants).

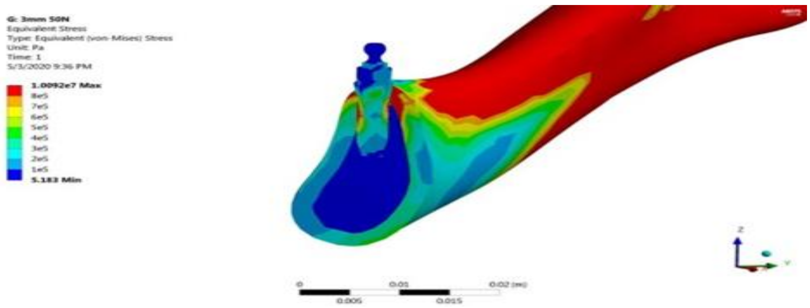

Figure 4. The stress distribution in the implant – attachment – bone system under bilateral vertical loading (3mm height differences between the implants).

Generally, the trabecular bone showed lower Von Mises stress values than the cortical bone. In bilateral loading conditions, lower stress values were recorded than unilateral loadings (verticallay and obliquely) in implants and the alveolar bone.

The minimum Von mises stress values were obsereved in vertical bilateral loading, and the maximum stress values were found in applying 100 N vertical load in the anterior rigion. In unilateral loading conditions, the stresses decreased by applying vertical forces in comparison with oblique loadings. In model 1, the stress value in the upper part of the lower implant by applying a unilateral vertical load was 2.5 MPa which was approximately 2.2 times lower than the stress value by applying a unilateral oblique load in this model (5.46 MPa; Table 3)

Table 3. Von Mises stress values in the left implant in FEA models of mandibular overdenture

Left implant	**Model 1**	**Model 3**	**Model 2**
Bilateral loading	0.33	0.71	0.34
Unilateral loading (vertical)	2.5	5.05	3.43
Anterior loading	8.5	10.8	9.9
Unilateral loading (oblique)	5.46	8.85	5.5

Table 4. Von Mises stress values in the right implant in FEA models of mandibular overdenture

Right implant	**Model 1**	**Model 2**	**Model 3**
Bilateral loading	0.34	0.41	0.74
Unilateral loading (vertical)	2.44	2.51	3.4
Anterior loading	10.2	12.25	14.4
Unilateral loading (oblique)	5.07	5.2	6.5

Discussion

Several biomechanical factors determine the stress distribution in bone-implant-attachment system, such as direction of force and bone density.

According to biomechanical studies, [20, 21] excessive force contributes to resorbtion of the crestal bone after loading. Clinicians should know about these factors and their effects on oral structures to control the functional loads and choose an optimal treatment plan for their patients.

In the present study, stress distribution in implants and the adjacent alveolar bone with different abutment heights was evaluated. The models in which the implants had up to 2 mm height difference with each other showed lower Von Mises stress values in comparison with the model with 3 mm height difference between the implants. These findings do not agree with the reuslts of Ozan and Ramoglu. [2]. They suggested that stress distribution in the alveolar bone was favorable with a height difference of 3 mm. The researchers acknowledge that these findings should also be verified in clinical conditions. [2]

The findings of the present study are probably related to the lever arm effect [22], which can also be justified by the amount of distance associated with the crown height space between the crestal bone and the occlusal plane. [23] There are two concerns about crown height space. [24] The first concern is about the space between the attachment system and the alveolar crest, and the second one is about the space between the attachment and the occlusal plane. Increasing the crown height space and lever arm effect in implant-supported overdentures leads to an increase in occlusal forces. According to Misch, in fixed prosthesis, for every 1 mm increase in crown height space, cervical forces increase by 20% and in removable prosthesis, by 1 mm increase in crown height space, cervical forces increase by 3.6%. [23]

In this study, more stress values were found in the higher implant (the right implant) in the anterior and bilateral posterior loading conditions in comparison with the left implant. It can be due to its higher position in bone, and this implant may be susceptible to crestal bone loss.

According to the results of the present study, the amount of von Mises stress values in different loading conditions in trabecular bone were less than cortical bone and the implant neck showed the highest concentration of stress among all areas analyzed in the implant, which is consistent with the findings of previous studies. [1, 18] Khurana et al. evaluated the stress distribution patterns in implant-supported overdentures with ball and locator attachments at 3 different heights. The stress values recorded in the cortical bone were higher than the trabecular bone, and the implant neck showed the highest Von Mises stress values compared with other parts of the implant. [1]

In the implant-attachment complex, the weakest area is the neck region of the fixture. The stress concentration increases in the contact area and close to the loading point, which is due to the materials with different modulus of elasticity and density in direct contact with each other. The cortical bone has higher density and modulus of elasticity in comparison with trabecular bone. The presence of two types of supporting bone (cortical and cancellous), which have different mechanical properties, is effective in creating such a stress pattern. [1, 25]

In the present study, more stress values were recorded by applying oblique loads than vertical loads. Non-axial loads cause the most unfavorable situation in dental implants and the alveolar bone. The amount of shear loads transmitted from the implant to bone increased by non-axial loads which is the most harmful component of force. [26] This result is consistent with several studies. [16, 27]

The main causes of bone loss around the implant-supported prosthesis include mechanical factors (excessive occlusal loads), infectious conditions (peri-implantitis and peri-implant mucositis), or a combination of them. During mastication, complex patterns of forces with different directions and magnitudes affect the stress distribution in the overdenture and bone-implant-attachment system. [28] In this study, the implants showed better stress distribution under bilateral loads than unilateral loads, which is consistent with the results of Alvarez-Arenal et al. [29] Dental clinicians should consider the bilateral balanced occlusion scheme and occlusal adjustments to prevent excessive loading of the alveolar bone and control the overdenture movements. It has been suggested that patients using implant-supported overdentures chew on both sides simultaneously. [30, 31, 32] Since the present study was performed in vitro using finite element software, it is necessary to verify the findings in clinical conditions.

Conclusion

In bone-implant-attachment system, lower values of Von Mises stress were found in the models with up to 2 mm difference in implant height. Lower stress values were found under bilateral forces in comparison with other loading conditions, and higher stress values were noted in cortical bone and the implant neck in comparison with trabecular bone.

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