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Original Article

Stress analysis of mandibular implant overdentures retained with one, two, or four ball attachments: A finite element study

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ABSTRACT

Background: The aim of this study is to compare stress patterns induced by ball attachments when used to retain mandibular overdentures supported by one, two, or four dental implants. **Materials and Methods:** In this finite element study, three 3D models were prepared to simulate mandibular implant overdentures retained by one or two or four ball attachments of 3.5 mm diameter with collar height 1.6 mm. The geometric solid models were created by commercial engineering computer-aided design package then transferred to ANSYS as set of standard ACIS text files. Vertical load of 100 N was applied on the central fossa of the right molar. Stresses were evaluated at the areas of implant and attachment components, mucosa underlying overdentures, and cortical and cancellous bone adjacent to implants.

Results: The results of this study showed that the Von Mises stresses generated by the application of vertical loading varied according to the number of implants used to support the overdenture. Maximum Von Mises stress on cortical bone ranged between 1.15 and 1.77 MPa in all-studied cases. Mucosa was squeezed under the one implant model. Flexibility of the overdenture material played a significant role in distributing the load stress and deformation of all underlying structure. Caps deformation was the highest when using two implants.

Conclusion: With increasing the number of implants, stresses and deformations of overdenture are reduced, but implants receive greater stresses and deformations. Using two implants in the canine region showed the best results when compared with using one or four implants, except for the caps.

Key Words: Attachments, finite element analysis, implant, overdentures, stresses

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INTRODUCTION

Implant-retained mandibular overdentures have been proven to be an effective treatment modality for restoration of missing teeth and nowadays are frequently used as a standard treatment for edentulous patients.[1]

Retention and stability problems of conventional complete dentures have been solved using implants-attachments-retained overdentures. Overdenture supported by 1–6 implants has become a common and effective procedure in the last decades.[2,3] Principally, the treatment planning should be selected according to the best available evidence. However, as economical factors play an

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essential role, it is important to be able to justify, how many implants should be used to effectively retain an overdenture in each individual case.

Many authors tried to address the question "how many implants should be placed with an implant overdenture for best treatment?" They found no answer because a solid evidence to address this topic is lacking.[4]

Some criteria were recommended for a successful treatment planning with implant-retained overdentures. These criteria are mainly interrelated to mandibular morphology, available bone height and width, required level of stability and retention, implants parallelism,[5] overdenture type, oral hygiene, maintenance procedures, maxillo-mandibular relationship, economical considerations, interimplant distance, and finally patient's compliance for recall and expectations in regards to psychological and esthetic considerations.[6,7]

Ball and socket attachments are widely used to support implant overdentures. Considering the small space requirements within prostheses to reduce possible mucosal hyperplasia, easy maintenance procedures, minimal chair time requirements, more economical incentives and lower sensitivity techniques, the unsplinted ball or locator attachments have been used with implant overdentures.[8-12] However, ball attachments experience some disadvantages as higher concentration of stress patterns at the neck of the ball transfer a greater amount of stresses to the implant and the underlying bone.[13] This is besides the problem associated with ongoing wear and tear of its components. Resin and metal clips and rubber O-rings can wear rapidly even with careful use and leads to reduced overdenture retention and thereby demanding replacement. Consequently, there is a need for frequent servicing of such overdentures.[14]

The number of implants required to ensure successful outcome with mandibular implant overdenture treatment remains debatable. It was pointed out that the value of fewer implants as a cost-saving approach has a merit for many patients. However, the use of more than two implants is recommended in certain cases so as to produce greater overdenture stability and preserving the supporting peri-implant bone.[15]

The finite element analysis (FEA) method offers several advantages, including accurate representation of complex geometries, easy model modification, and representation of the internal state of stress and other mechanical qualities. It is considered a valuable tool to predict, adjust, and prevent future failures in standardized circumstances of research studies.[16] The aim of this study was to compare the stress patterns induced by ball attachments when used to retain mandibular overdentures supported by either one or two or four implants. The null hypothesis to be tested was that there are no significant differences in the stresses generated by ball attachments retaining mandibular overdentures supported by either one or two or four implants.

MATERIALS AND METHODS

This finite element study simulates a clinical situation where an edentulous mandible was restored with an implant supported overdenture. Based on Jianping *et al*.,[17] three 3D finite element models were prepared specially for this study. The models were created based on the number and location of implant(s) as follows:

1. One implant in the midline region
2. Two implants in the canine regions
3. Four implants; two in the canine regions and two in the first premolar regions.

The geometric models were created on "Autodesk Inventor" Version 8 (Autodesk Inc., San Rafael, CA, USA), then exported as standard ACIS text files. These models' components were assembled in ANSYS environment (ANSYS Inc., Canonsburg, PA, USA). The system analyzed in this investigation consisted of the commonly available root form-threaded titanium dental implant (Zimmer dental Inc, USA) with ball attachment (3.5 mm diameter with collar height 1.6 mm, Zest Anchors, Zimmer dental, USA). The root form dental implant had a nominal diameter of 3.7 mm, a length of 13 mm and the shape of internal hex with a hex width of 3.5 mm.

Peri-implant bone including an inner layer representing cancellous bone of 22 mm height and 14 mm width covered by outer thin layer of cortical bone of 2 mm thickness, while the covering mucosal layer of 2 mm thickness. The acrylic overdenture was simulated of a height 8 mm and width of 8.73 mm.[18,19] Perfect osseointegration was assumed to be presented between implants and bone. All materials were assumed to be isotropic, homogenous, and linearly elastic and its properties are listed in Table 1. The lowest plane of each model was considered as fixed nodes in the three directions as a boundary condition as recommended by Brunski.[25]

Set of Boolean operations between the modeled components were performed before obtaining the complete model(s) assembled (Boolean operation is an option presents in FEA system; it helps to mask all types of material complementing each other to ensure complete contact of all elements as they all constitute the full density mask). Meshing of these components was done by 3D brick solid element "Solid-45" which has three degrees of freedom (translations in main axes directions). The resulted numbers of nodes and elements are listed in Table 2, and samples for these meshed components are presented as screen shots from ANSYS screen in Figure 1.

For each model, 100N vertical loading was applied on the area of the first molar on the right side to simulate the natural masticatory condition in dentulous patient where they put the bolus of food on one side. Linear static analysis was performed on a personal computer (Intel Core to Duo processor, 2.8 GHz, 4.0 GB RAM), using commercial multipurpose finite element software package (ANSYS version 12.0) (ANSYS Inc., Canonsburg, PA, USA).[26] As the study will not discuss fracture of any component, the linear part of each material was calculated as follow:

Table 1: Material properties used in the finite element model

Material	Young's modules (MPa)	Posison's ratio
Acrylic resin overdenture[20]	2700	0.35
Mucosa[21]	10	0.40
Nylon ring (cap)[22]	350	0.40
Implant complex[23]	110,000	0.35
Cortical bone[24]	13,700	0.30
Cancellous (spongy) bone[24]	1370	0.30

Table 2: Number of nodes and elements in all meshed components

Component	1× ball attachment		2× ball attachment		4× ball attachment	
	Nodes	Elements	Nodes	Elements	Nodes	Elements
Overdenture	852	10,674	2056	7287	2796	9658
Mucosa	1907	3908	2594	7470	4410	13,574
Nylon ring (cap)	1767	6827	2388	10,264	4788	2603
Implant complex	19,665	1,333,718	56,922	317,994	96,216	516,713
Cortical bone	1934	5890	1769	4892	2177	5844
Spongy bone	1820	20,166	8307	29,486	16,356	58,867

Stress = Young's Modulus × Strain

where:

Stress (Force [N]/Area [mm^2])

Young's Modulus (slope of linear part of stress-strain curve [MPa = N/mm^2])

Strain (deformation [mm]/original dimensions [mm])

The term total deformation (U_{sum} or U_{total}) represents the resultant deformation for directional deformations (U_x, U_y, U_z) as;

$$U_{sum} = \sqrt{U_x^2 + U_y^2 + U_z^2}$$

The solid modeling and FEA were performed on a personal computer Intel Pentium IV, processor 2.8 GHz, 1.0 GB RAM. The meshing software was ANSYS version 12. The results of these models were verified against similar studies.[17,27]

RESULTS

The locations and values of stresses under loading were detected in all model components separately, where the generated total deformation and Von Mises stresses in all cases were compared. FEA calculations showed that the overdenture total deformation of the model with one ball and socket attachments, was about double the four implants and about 50% more than using two attachments [Figure 2].

Figure 3 shows high Von Mises stress values on the ball attachment neck close to the applied load in all cases and increases with increasing the number of implants.

Figure 4 compares all components total deformation and Von Mises stresses. It is shown that there was superiority for using two attachments over using one or four attachments when looking to mucosa and overdenture deformations. Both cortical and cancellous bone were not sensitive to the number of implants. Using one implant showed lowest value of Von Mises stress in the implant complex and highest overdenture stress.

DISCUSSION

Currently, implant-retained overdentures have become one of the most preferred options for the treatment of completely edentulous patients.[28] Implant-retained overdentures have various attachment systems including bar-clip, ball, bar ball, O-ring, and magnet.

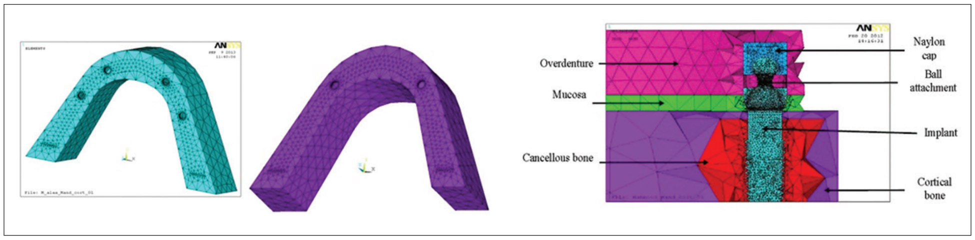

Figure 1: Meshed components of the used models.

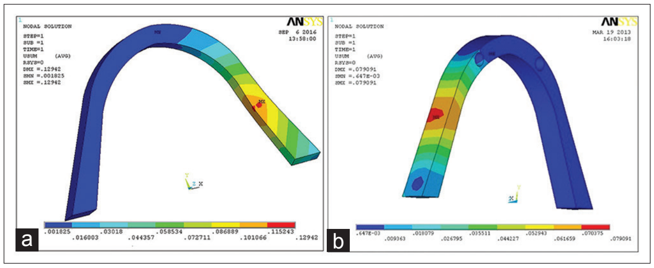

Figure 2: Overdenture total deformation in cases of using (a) one and (b) two ball and socket attachment.

The forces resulted from mastication are transferred to implants and produce stress in peri-implant bone. Two to four implants are used in the interforaminal region to support mandibular overdentures.[29]

According to Grageda and Rieck,[30] a single implant mandibular overdenture significantly increases patients' satisfaction and quality of life.

The influence of implant number on biomechanical behavior of mandibular implant retained/supported overdentures was studied by Liu *et al*.[19] through three-dimensional FEA.

An implant-supported overdenture is subjected to various types of axial and nonaxial stresses, including the masticatory forces. The resultant of these forces is transmitted through the superstructure and the attachments to the implants and may lead to concentration of stresses in the different parts of the implants.[31]

FEA is a mathematical method; cannot fully represents the complexity of the biological field. It assumes that the structures are homogenous, linear, elastic, and isotropic. The dental structures as bone and periodontal ligaments are nonhomogenous, viscoelastic, and anisotropic which make the calculated values relative rather than absolute. FEA lacks the knowledge of the amount of stresses at which biological changes such as resorption or deposition of bony structures occurs, which makes it difficult to obtain a definite conclusions. Most FEA models assume a state of optimal osseointegration that both cortical and cancellous bone are perfectly bonded to the implant and that does not actually happen in the clinical conditions.[32]

FEA can simulate the interaction phenomena between implants and the surrounding structures if detailed information regarding geometry of bone, implant geometry, length, diameter, and shape as well as the boundary conditions and the nature of bone-implant interface are supplied to the computer.[33] In spite of inherent limitations of finite-element analysis, it has been considered a valuable tool to study stresses at implant and implant-bone interface.[34]

The results of FEA coupled with the findings of clinical studies may provide reliable data regarding stresses transmitted to implant and/or on bone-implant interface.[35]

The results of the present FEA revealed that the highest stresses in peri-implant bone concentrate around the neck of the implants (i.e., cortical bone). This result has been also reported in other past studies for other configurations.[28,36]

The results of this study revealed that the stresses induced at the implant-bone interface after load application was not high in cortical and cancellous bone in the studied models [Figure 4]. This finding may be due to the excellent retentive quality of the ball attachments that absorb most of applied forces and the implant strategic position especially in two implant overdenture models which allows least stresses to be transferred to bone around implants. Moreover, ball attachment system is resilient, the stress in the bone around the implant is subsequently lessened and part of the stress is transferred to the posterior ridge; this results in better stress distribution and thus reduces the maximum stress level.[37]

The results revealed that the simulated mucosa had undergone high deformation in the studied model of single implant-retained overdenture; this may be attributed to the high stresses transmitted to that

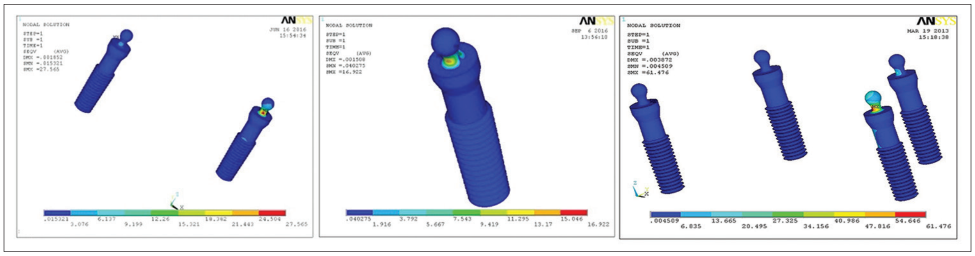

Figure 3: Ball and socket attachment Von Mises stress with different number of implants.

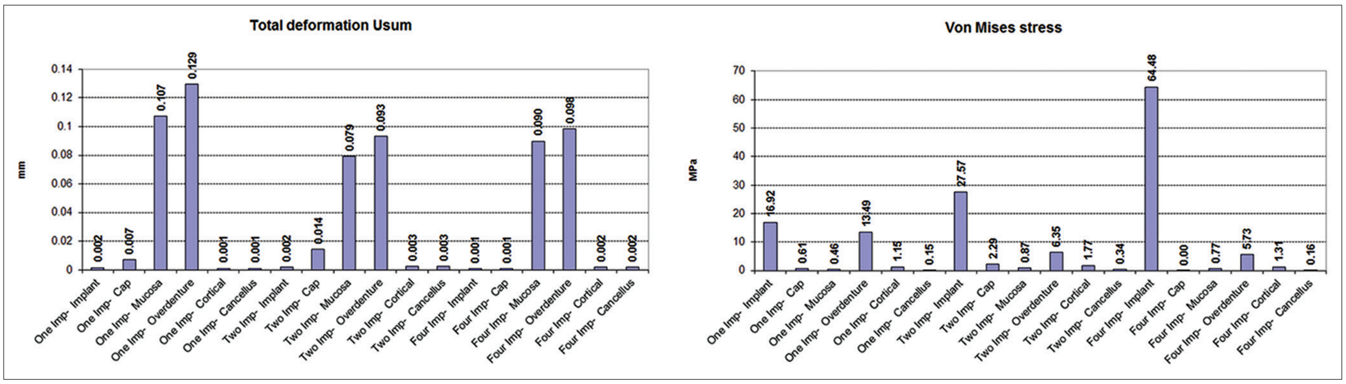

Figure 4: Comparison between total deformation and Von Mises Stress in all cases.

part as it is embedded between overdenture base and underlying bone. The high-stress values may be attributed to the heavy stresses transmitted onto the overdenture by the unilateral load application with the presence of only single implant with one ball attachment that may play only a minor role in distribution of the applied load. Consequently, the applied load mostly carried-by the overdenture and transmitted to the underlying mucosa as occurred in the present study. The use of two implants with corresponding ball attachments had resulted in superior stress distribution patterns than one or four implant overenture models regarding mucosa and overdenture deformations. This finding may be due to load dissipating quality of the ball attachments and especially when they are in strategic position as in two-implant overdenture wherever implants were installed in the interforaminal region.[38,39]

Moreover, the flexion of the overdenture in the mandibular interfominal area may be minimal due to the presence of two implant support as well as the excellent retentive quality of the ball attachments that leads to less tissue-ward movement of the overdenture and consequently less stresses to underlying mucosa and bone. It was found that on unilateral loading, with ball/O-ring, attachment the strain was concentrated on the loading side implant. This is because the ball attachments are not splinted together and react to load separately.

These results were consistent with previous studies that noted that the axial force on the loading-side implant was minimal with the Ball/O-ring attachment. This may be the result of the stress-absorbing effect of the rubber O-ring component as reported by the previous studies.[40-42]

Within the limitations of FEA, in which ball attachments were used, minimum amount of force was transmitted to the implant body. The load may have been absorbed at the rubber O-ring component and anchor head connection. Therefore, in the long term, prosthetic complications such as screw loosening or the need to replace O-ring matrices may occur.[24,43]

CONCLUSION

Within the limitations of this study, it may be concluded that increasing number of implants reduces the overdenture stresses and deformations while implants receive more stresses and deformations. On the basis of available data, it is difficult to demonstrate that a particular number of implants offered better outcome as compared to another. This should not be interpreted as meaning that implant supported overdentures are ineffective. In general, using two implants in the canine region showed the best results when compared with using one or four implants, except for the caps. That may result in relatively short period between successive maintenances.

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Conflict of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial, or nonfinancial in this article.

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