Original Article

A Finite Element Study to Analyze and Compare the Stresses Generated in the Bone Distal to Implants Using Different Designs and Biomaterials as Attachments in a Mandibular Implant-Retained Overdenture

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Abstract

Background: Implant-retained overdentures are associated with disadvantages like increased ridge resorption observed in the bone distal to implants which pose a major clinical challenge making the successful use of an IRO difficult. The purpose of this study was to find out ways to reduce the resorption rate by varying attachment parameters. **Materials and Methods:** This study utilized the tool of finite element analysis. The data acquired from computed tomography of an edentulous mandible and the physical models of locator and ball attachments was used to construct eight distinct finite element models. The models varied in either the design or the biomaterial used for the fabrication of the attachment or in the direction of loading. All the models were finally subjected to forces and von Mises stresses generated were calculated and comparatively analyzed and interpreted. **Results:** They were obtained in color coded and numerical form as von Mises stress values. **Conclusion:** The locator attachments showed marginally higher stress concentration in the distal bone as compared to ball attachments. The material of the attachment did not influence the bone stress, but the stress concentration in the implant fixtures was affected.

Keywords: Implant-retained overdenture, Ball and locator attachments, Residual ridge resorption, Finite element analysis.

Introduction

Edentulism presents with debilitations such as compromised chewing, altered phonetics, and psychological effects like reduced self-esteem which need to be addressed prosthetically with urgency. A conventional complete denture over a severely resorbed mandibular ridge often originates complaints of inadequate retention and denture instability during function. A satisfactory and economically sound approach is the use of implant-retained overdentures. It has in fact been declared as the minimum standard of care for the completely edentulous patient as given under the Mc Gill and York consensus.[1,2] IRO leads to positive dynamic bone remodeling due to the higher bite forces of up to 300%. The superiority in retention and support offered by IRO is due to the secured and anchored nature of the implants. The masticatory forces are taken up and absorbed by the implant fixtures and the implant attachments act as the conduits that let these forces pass from the denture teeth and base material, through them to the areas where they can be absorbed and tolerated well. However, due to the lack of proprioceptive impulse feedback, the patients are not able to regulate their bite force and it has been observed that such uncontrolled forces, over time, can lead to alarming rates of bone resorption causing abuse atrophy of the biological tissues.[3] Hence, the success of IRO is basically governed by the mechanics of forces subjected on the implant assemblies.[4] This, in turn, is influenced by the geometry and material characteristics of the attachment system between the endosseous implant and the prosthesis.[5] Hence, in this study, both the geometric shape and the material of the attachments were varied and results were observed and analyzed.

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Materials and Methods

To evaluate and compare the biomechanical performances of two different designs (ball and socket and locator) and two discrete materials (Grade 04 titanium and PEEK) of implant attachments for a mandibular overdenture, the tool of finite element analysis[6-8] was used.

The spiral computed tomography (CT) scan was used to record the data obtained from the whole skull of an edentulous person and visualized and segmented using the Mimics 8.11 software. The mandibular data were extracted from the skull and exported as an STL file. It was, then, converted to geometric models of the mandible using Rapid Form 2004 software. The geometric models for each attachment design were also created at the same time but modeled separately using the tool of reverse engineering by measuring the dimensions of the physical parts using precision measuring tools. The files of the mandible and the attachments were imported separately into HyperMesh 13.0 software and assembled at previously determined positions. Thus, the geometric models were converted to eight different finite element models by a process called meshing which were as follows:

Design 01: An overdenture retained by two ball abutments made of Grade 4 titanium tested under the vertical loading of 100 N between the second premolar and first molar.

Design 02: An overdenture retained by two ball abutments made of PEEK tested under the vertical loading of 100 N between the second premolar and first molar.

Design 03**:** An overdenture retained by two ball abutments made of Grade 4 titanium tested under an oblique loading of 100 N at 30° angulation between the second premolar and first molar in the buccolingual direction.

Design 04: An overdenture retained by two ball abutments made of PEEK tested under an oblique loading of 100 N at 30° angulation between the second premolar and first molar in the buccolingual direction.

Design 05: An overdenture retained by two locator attachments made of Grade 4 titanium tested under the vertical loading of 100 N between the second premolar and first molar.

Design 06: An overdenture retained by two locator attachments made of PEEK tested under a vertical loading of 100 N between the second premolar and first molar.

Design 07: An overdenture retained by two locator attachments made of Grade 4 titanium tested under the vertical loading of 100 N between the second premolar and first molar.

Design 08: An overdenture retained by two locator attachments made of PEEK tested under an oblique loading of 100 N at 30° angulation between the second premolar and first molar in the buccolingual direction.

In the HyperMesh software, different material properties (Young's Modulus and Poisson's Ratio) were assigned to each component of the model in addition to application of loads and boundary conditions. The values were obtained from pre-existing literature. All the models were subjected to vertical and oblique forces (30°) of 100 N magnitude in the area between the second premolar and the first molar.

The study parameters that were chosen for the present study were constant for each model such as:

Mucosal thickness: 2 mm
Cortical bone thickness: 1.25 mm
Quality of trabecular bone: D2
Implants: Tapered internal hex bone level implants placed in the two canine regions, 3.2" × 10" in dimensions
Implant material: Ti6Al4V alloy
Implant attachments: Grade 4 Titanium and PEEK
Design of attachments: Ball and locator both with 01 mm collar height
Inter canine width: 28 mm

Results

The results were recorded and analyzed in numerical form as von Mises stresses (calculated in MPa). The high stress areas were seen color coded as red in the models and the low stress areas were shaded blue. The intermediate stress zones were coded in green and yellow (Figures 1 and 2).

For ball attachments under vertical loads, the stress values were 10, 1.6, 1.53, 1.49, 3.18, and 0.67 for denture, mucosa, ball attachment, implant body, cortical bone distal to implants, and cancellous bone distal to implants, respectively, while using Grade 4 titanium as the material for the attachments. In case of inclined loading, the stress values for the same areas and same material came out as 12.73, 1.63, 4.3, 3.9, 6.37, and 0.85 respectively. The results for ball attachments using PEEK as a material under vertical loading were 10, 1.6, 0.37, 1.92, 3.18, and 0.67 and the same under oblique loading was 12.73, 1.64, 1.02, 5.47, 6.51, and 0.72, respectively.

For locator attachments made of Grade 4 titanium, the von Mises stresses calculated under vertical loading were 12.48, 1.73, 3, 2.27, 7.27, and 0.67 and under oblique loading was 12.98, 1.77, 9.27, 7.1, 7.6, and 0.78. The forces calculated for the same locator attachments made out of PEEK under vertical loading came out to be 12.48, 1.73, 0.43, 7.36, 7.27, and 0.69 and under oblique loading was 12.98, 1.77, 1.06, 21.74, 7.64, and 0.9.

The tabular representation of the results is shown in Tables 1 and 2.

Discussion

Mandible due to its meager blood supply and force concentration on a relatively smaller surface area shows greater bony resorption as compared to maxilla, thus creating an unfavorable foundation for a conventional complete denture. Therefore, a two-implant-retained mandibular overdenture has been established as a minimum standard of care for an

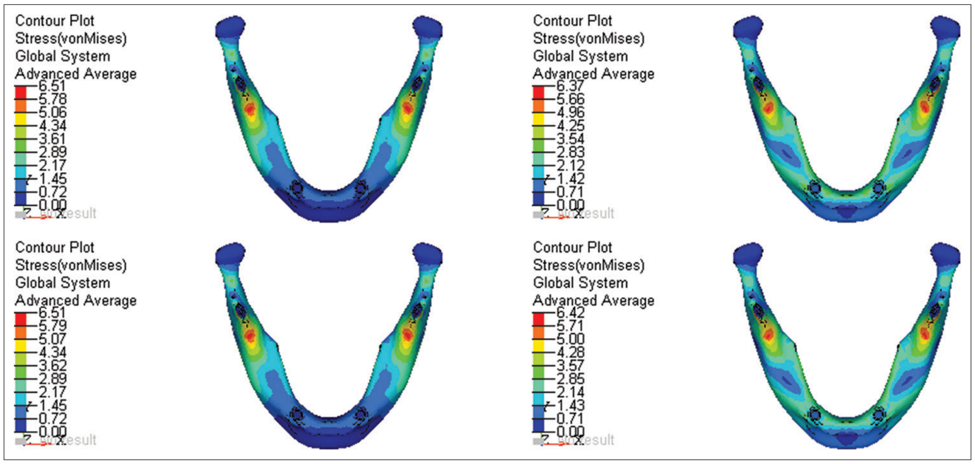


Figure 1: Stresses in the cortical bone distal to implants as observed in this color-coded image while subjecting ball attachments made of Grade 4 titanium and PEEK materials to axial and inclined loads

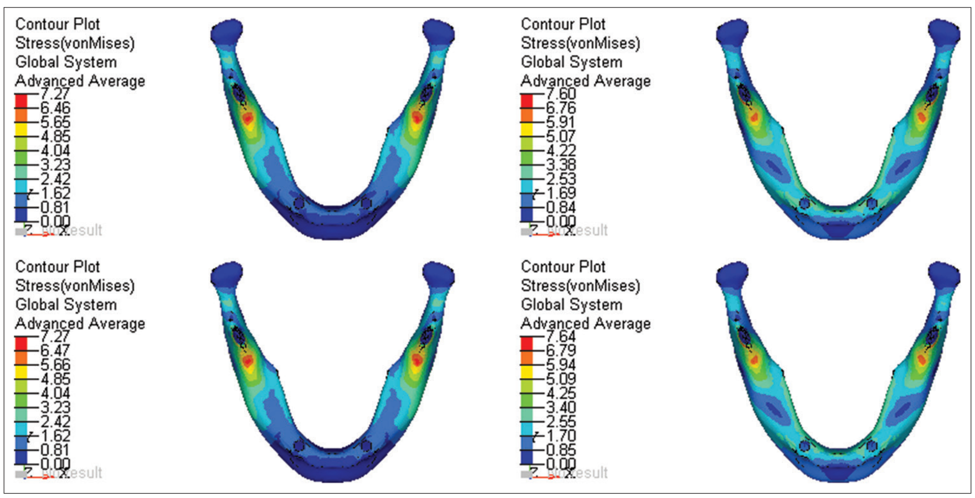


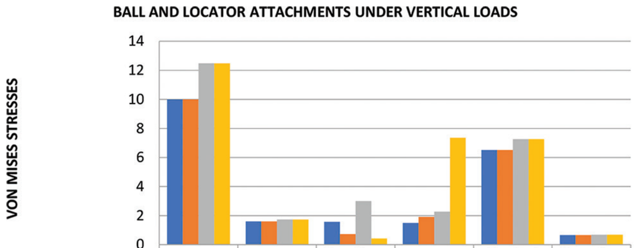
Figure 2: Stresses in the bone distal to implants as observed in this color-coded image while subjecting locator attachments made of Grade 4 titanium and PEEK materials to axial and inclined loads

edentulous patient.[1,2] This increases the retention and stability of the denture and also enables the patient to chew with increased bite forces. In spite of these short-term advantages, there is one long-term disadvantage associated with the use of an IRO. Because it gains most of its support from the denture bearing mucosa distal to the implants, the resultant stresses cause hydrostatic pressure build-up in the mucosa secondary to minor cyclic trauma that leads to intracellular and intercellular edema. This compresses the periosteal blood vessels, further reducing nourishment, leading to bony resorption in the areas distal to the implants.[3] There are many variables that can be altered to a prosthodontist's advantage to attain a favorable prosthetic prognosis for an IRO in the long run. In the present study, keeping all the other parameters constant, the design, and material of the attachment abutments were varied to analyze its effect on the stresses generated within the implant systems, the peri-implant bone, and the distally located bony foundations.

Grade 4 titanium, commercially pure titanium, and titanium alloys have been used in implant dentistry since its inception. However, due to the higher modulus of elasticity (MOE) of the titanium alloys, it is perceived to induce greater stresses in the bone. The MOE of PEEK, a polymeric material, gaining popularity in contemporary dentistry, parallels that of bone and thus is expected to generate lesser stresses and act as a better conduit for force transmission from the prosthesis to the bone through the implant bodies.[5]

As per results of this study, the load transmission from the ball attachments to the implant body was observed to be 1.49 MPa. This showed that the Grade 4 titanium ball attachments retained more stresses within the attachment than were led on to the implant body. In case of locator attachments, the stress profile of the implant body showed a value of 2.27 MPa. Comparatively, although the stresses were greater in the implant body in case of locator attachments, the Grade 4 titanium material was following the same stress gradient for both designs. Furthermore, in both cases, the stress accumulation was in the area of the neck of the implant which was in accordance with some previous studies.[9,10] It is

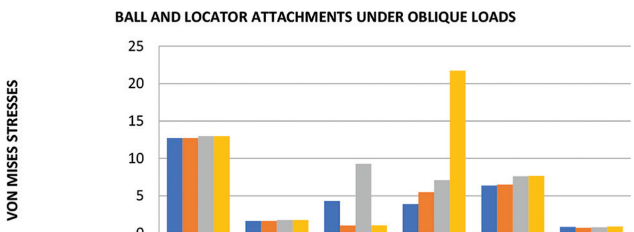
Table 1: Numerical values for the von Mises stresses observed under axial loads at various positions in the denture load bearing areas



	Denture	Mucosa	Attachment	Implant	Cortical bone	Cancellous bone
Grade 04 Ti Ball	10	1.6	1.57	1.49	6.51	0.67
PEEK Ball	10	1.6	0.73	1.92	6.51	0.67
Grade 04 Ti Locator	12.48	1.73	3	2.27	7.27	0.69
PEEK Locator	12.48	1.73	0.43	7.36	7.27	0.69

Grade 04 Ti Ball ■ PEEK Ball ■ Grade 04 Ti Locator ■ PEEK Locator

Table 2: Numerical values for the von Mises stresses observed under non-axial loads at various positions in the denture load bearing areas



	Denture	Mucosa	Attachment	Implant	Cortical bone	Cancellous bone
Grade 04 Ti Ball	12.73	1.63	4.3	3.9	6.37	0.85
PEEK Ball	12.73	1.64	1.02	5.47	6.51	0.72
Grade 04 Ti Locator	12.98	1.77	9.27	7.1	7.6	0.78
PEEK Locator	12.98	1.77	1.06	21.74	7.64	0.9

Grade 04 Ti Ball ■ PEEK Ball ■ Grade 04 Ti Locator ■ PEEK Locator

important to note that in case of Grade 4 titanium attachments, the load transfer to the implants was well under the critical values for fracture toughness of titanium alloys (28–108 MPa) under cyclic loading. These results were consistent with studies by El-Anwar *et al*.,[4] yet in conflict with the study by Khurana *et al*.,[2] where higher stress levels were seen with the use of ball attachments.

It was also observed that significantly higher stress levels were recorded with inclined loading as compared to vertical loading. Greater stress accumulation was recorded in the prosthesis and mucosa as compared to the cortical and the cancellous bones distal to the implants which were the target area of the study. A higher level of stress was again observed with locator attachments than ball and socket models. A possible explanation for this could be the unique matrix-patrix relationship of locator attachments and the shape of the ball attachment that has been suggested to be prone to absorbing more stresses rather than dissipating.

Taking the area of interest into consideration, the results showed almost identical levels of stress in the bone distal to the implants for both the designs of the abutments with forces being only 0.76 MPa higher for the locator attachments.

PEEK attachments showed little stress accumulation within the abutment itself as compared to Grade 4 titanium abutments. The stress value within the PEEK ball attachment was 0.37 MPa and 1.02 MPa for axial and non-axial forces, respectively, as opposed to 1.57 MPa and 4.3 MPa for Grade 4 titanium ball abutments. The locator design exhibited a steeper gradient in the stress accumulation as compared to the ball attachments. Thus, it could be concluded that PEEK locators are more efficient stress transmitters.[10-13]

The alarming detail with the use of PEEK attachments of both the designs was the quantity of stresses transferred to and concentrated within the implant fixture at the neck. The values were 1.92 and 5.47 MPa for ball and 7.36 and 21.74 MPa for locator attachments. Here, steeper gradient could again be appreciated in case of PEEK locators as opposed to the PEEK ball and socket attachments. The large loads transferred to Ti6Al4V implants are not as easily dissipated to the surrounding bone due to high MOE of the alloy and hence get concentrated within the implants, leading to high chances of fracture at the implant-abutment junction. It could, hence, be deduced, that with the application of inclined loading and the use of PEEK locator abutments, the stresses concentrated in the implant fixture were nearer to the critical values (28 MPa–108 MPa) for component fracture. This is an area of grave concern.

The considerable increase in the amount of forces the implant fixture is subjected to when PEEK attachments are used in place of the titanium abutments, which is noteworthy. It can thus be concluded that when similar kinds of materials are used for the implant body and attachment, the load sharing of the system is much better than when dissimilar materials are utilized.

Comparing the stress patterns in the peri-implant bone and the bone distal to the implants, the peri-implant cortical bone exhibits lower stress levels as seen in the cortical bone distal to the implants. The varying of the attachment geometries and the materials did not have any appreciable effect on the stresses as calculated in the distal bony zones. The solution is augmenting the implants with greater numbers in the posterior mandible that would relieve stresses on the mucosa displaying better load sharing mechanics.[6,14-16] Another scope is in the use of PEEK as a material for both the implant fixture and the attachment above. This might lead to greater time-controlled release of stresses to the peri-implant bone reaching the distal bony zones after getting dampened, thus somewhat equalizing the stresses calculated in peri-implant and distal bones.

The most important factors to take care of while planning an IRO still remain the placement and angulation of the implants and the planned occlusion of the prosthesis. These, when planned well in advance, will keep the prosthesis and implant systems subjected predominantly to axial forces cutting down on the induced stresses considerably.[7,8,17-20] Keeping all limitations of the present study in view, it can be deduced that this study is good for a comparative analysis for the different parameters of the study under observation. It did not, however, provide any absolute values for the stresses. Hence, further studies in the same area coupled with long-term clinical trials are suggested to correlate the findings of the study with what happens clinically in the situations under the same parameters.

Conclusion

Within the limitations of the study, the following conclusions can be drawn:

The geometry or design of the attachment does influence the stresses generated in the bone distal to the implants.

According to the results obtained from this study, the locator attachments showed marginally higher stress concentration in the bone distal to the implants as compared to when ball attachments are used.

The material used for attachment fabrication does not influence the stresses generated in the bone distal to the implants, but it does influence the stress concentration seen in the implant fixtures in the implant abutment junction area.

With the use of PEEK material, lesser concentration of stresses is seen in the abutment per se, but more stress concentration is observed in the titanium implants particularly around the neck area of the body of the implant. The stress profile in the bone distal to the implants remains somewhat constant.

The stress profiles on the ipsilateral and contralateral sides of the load application were observed to be fairly similar and showed no wide margin.

There is scope for further studies using PEEK as the material of choice for both the implant fixture and the attachment abutment to analyze the stress patterns in the bone distal to the implants.

There is scope for introduction of more number of implants in the assembly and analyze the generated stress patterns in the bone of the residual ridge.

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