Stress analysis of mandibular implant-retained overdenture with independent attachment system: effect of restoration space and attachment height

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In this in vitro study, 2 implants were embedded in the interforaminal region of an acrylic model. Two kinds of retention mechanisms were used to construct complete overdentures: ball type and direct abutment (Locator). The ball-type retention mechanism models included 3 different collar heights (1, 2, and 3 mm) with 15 mm occlusal plane height, and 3 different occlusal plane heights (9, 12, and 15 mm) with 1 mm collar height. The direct abutment models included 3 different occlusal plane heights (9, 12, and 15 mm) with 1 mm cuff height. Vertical unilateral and bilateral loads of 150 N were applied to the central fossa of the first molar. The stress of the bone around the implant was analyzed by finite element analysis.

The results showed that by increasing vertical restorative space, the maximum stress values around implants were decreased in both unilateral and bilateral loading models. The results also showed that the increase in maximum stress values around implants correlated with the ball attachment collar height. The Locator attachment with a 1 mm cuff height and 9 mm occlusal plane height demonstrated 6.147 and 3.914 MPa in unilateral and bilateral loading conditions, respectively. While a reduction in the collar height of a ball-type retention mechanism and an increase in the vertical restorative space in direct abutment retention mechanisms are both biomechanically favorable, and may result in reduced stress in peri-implant bone, a ball attachment seems to be more favorable in the stress distribution around an implant than a Locator attachment.

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The restoration of an edentulous mandible with an overdenture supported or retained by 2 implants is considered to be the primary prosthetic treatment approach.[1] The retention and stability of prostheses are provided primarily by implants through attachments.[2,3] Various types of attachments have been suggested for implant-supported overdentures. Independent or dependent connection of implants through ball, O-ring, Locator, and bar attachments are the most common approaches.[2-5] Some studies have reported implant support via ball-type attachments as a reliable treatment.[3,6-10] The freedom of rotation within the ball attachment allows for stress release. The method of retaining overdentures by 1 or 2 implants using resilient attachments is a relatively simple and inexpensive method to reconstruct an edentulous mandible.[11]

Selection of the optimal attachment is dependent upon the required retention, jaw morphology and anatomy, oral function, and patient compliance for recall.[12] The ball attachment places less stress on implants and produces less bending movement in comparison to the bar-clip attachment.[3] The Locator, which is self-aligning and has dual retention, is another type of independent attachment. It is available in various vertical heights, and its resiliency, retention, and durability are favorable.[12] The effect of a resilient or rigid attachment system on retention and stress distribution is a subject of controversy in the literature.[12-16] Biomechanically, the advantages of implant splinting are unclear. The rationale of implant splinting was that it would decrease stresses due to increased prosthesis stability.[17,18]

Adequate restorative space is another important factor in successful implant-retained overdenture treatment.[19] In edentulous patients, available restorative space is bounded by the supporting tissues of the edentulous jaw, cheeks, lips, tongue, and the occlusal plane. Other factors must also be considered when defining available restorative space, such as interocclusal distance, phonetics, and esthetics.[20]

The minimum vertical restorative space required for an implant-supported overdenture is 8.5 mm for Locator attachments, 10-12 mm for ball and O-ring attachments, and 13-14 mm for bar-clip attachments.[20]

The distance from the crest of the alveolar bone to the plane of occlusion in implant-supported prostheses is defined as the crown height space (CHS). The biomechanics of CHS is related to lever arm mechanics.[21] Nonaxial loading creates a lateral moment which proportionally increases with increased CHS; this results in stress concentration at the bone surrounding the implant neck.[22] Increasing the CHS by 1 mm results in a 20% increase in the cervical load on a fixed-implant prosthesis. Implant splinting has been suggested to overcome the biomechanical overload in this situation. However, implant splinting in fixed-implant supported prostheses has not been proven to significantly improve implant success rates.[23]

Fabricating an implant-supported overdenture requires an adequate space for restorative components.[19] Evaluation of space limitation after implant surgery allows for appropriate attachment selection. Inappropriate treatment planning before placing a removable implant-supported prosthesis can lead to problems such as overcontoured or fractured prostheses. Two height levels should be considered in any removable prosthesis with mobility and soft tissue support: the first is the height of the attachment system to the crest of the bone, and the second is the distance from the attachment to the occlusal plane.[21]

In a finite element analysis (FEA) study, Ebadian et al evaluated different vertical restorative spaces and different bar heights of mandibular overdentures, and showed

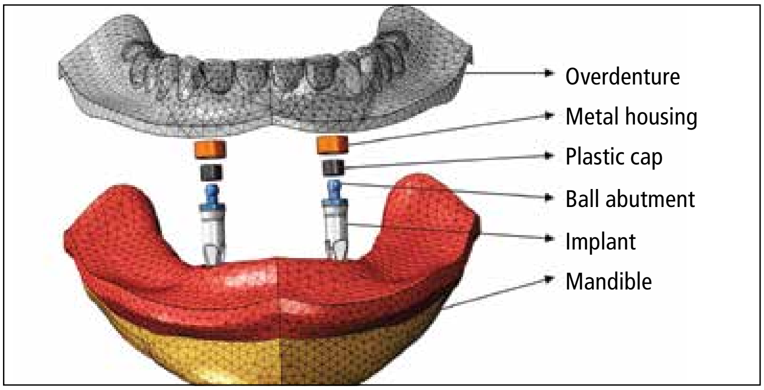

Fig. 1. Computerized mesh modeling showing jaw and overdenture with ball attachment.[24]

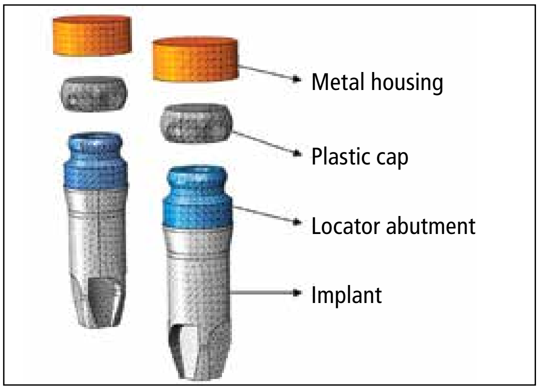

Fig. 2. Computerized mesh modeling showing Locator system.[24]

Fig. 3. Modeling of 3 different occlusal plane heights.[24]

that increasing the vertical restorative space and decreasing the bar height led to a decrease in the maximum stress value around the implants when a unilateral load was applied.[24]

Since the use of independent attachments in different occlusal plane heights is not well-defined, the purpose of this study was to evaluate the effect of different vertical restorative spaces (that is, occlusal plane distance to gingival level) and different ball attachment collar heights on the stress distribution around implants by 3-dimensional (3D) finite element analysis.

Materials and methods

In this in vitro study, the experimental design included the fabrication of a simulated 2-implant-retained mandibular overdenture. For this purpose, an acrylic model of an edentulous mandible was fabricated with a clear acrylic resin (Meliodent Multicryl, Heraeus Kulzer). The configuration of the bone was duplicated from an edentulous mandibular skeleton. Two screw-type implants, 4 x 10.5 mm with a 4.5-mm-diameter abutment platform (Biohorizons Internal, BioHorizons IPH, Inc.), were embedded in the interforaminal region of the acrylic model using a surveyor (Ney Surveyor, DENTSPLY International). The implants were vertically oriented, perpendicular to the occlusal plane, and parallel to each other. The crestal bone position of the implants was on the top of the ridge. The interimplant distance was 20 mm. Two types of retention mechanisms were used in this study: a ball attachment with plastic matrix and metal housing (BioHorizons IPH, Inc.), and a direct abutment attachment with plastic matrix and metal housing (Locator attachments, 4.5 mm with a 1.0 mm cuff, BioHorizons IPH, Inc.) (Fig. 1 and 2).[24]

Based on the laboratory design used by Ebadian et al, a complete overdenture was fabricated on these attachment models.[24] The plastic model, acrylic denture, implants, Locator and ball attachments were used for computerized reproduction. To improve analysis, the implants were considered as flat cylinders. The 3D geometry of the entire system was scanned and digitized using ATOS II (Triple Scan) scanning technology (GOM mbH) and viewer software (ATOS version 6.3.0, GOM mbH). Implants were assumed to be completely osseointegrated, so that a mechanically perfect interface—to ensure the continuity of displacement and traction vectors—was pressured between implants and bone. Other contacts existing between the elements were also assumed to be perfect. The resultant dense point cloud was transferred to CATIA modeling software (Dassault Systemes Americas Corp.). The geometry was then meshed by tetrahedral linear elements.

The mucosa and cortical bone were reproduced as a 2 mm and 2.5 mm layer, respectively. Three different collar heights (1, 2, and 3 mm) with a 15 mm occlusal plane height, and 3 different occlusal plane heights (9, 12, and 15 mm) with a 1 mm collar height were modeled for the ball attachment system (Fig. 3). Three different occlusal plane heights (9, 12, and 15 mm) with a 1 mm cuff height were modeled for the Locator system. Thus, 9 models were obtained. The value of friction coefficient was fixed to 0.02.[25]

Table 1. Mechanical properties of the prosthesis, implant, and bone materials used in this study.[13,27-30]

Material	Young modulus (Pa)	Poisson ratio
Cortical bone	1.37×10^{10}	0.30
Trabecular bone	1.37×10^{9}	0.30
Mucosa	1.0×10^{7}	0.40
Acrylic resin	2.7×10^{9}	0.35
Titanium	1.17×10^{11}	0.33
Gold	1.0×10^{11}	0.30
Rubber	5×10^{6}	0.45

Table 2. The number of elements and nodes in the ball attachment models.

Occlusal plane height (mm)	Collar height (mm)	Number of elements	Number of nodes
9	1	147,640	40,898
12	1	155,058	42,095
15	1	161,329	43,240
15	2	164,140	43,828
15	3	166,287	44,355

Table 3. The number of elements and nodes in the Locator attachment models.

Occlusal plane height (mm)	Cuff height (mm)	Number of elements	Number of nodes
9	1	176,967	50,772
12	1	184,234	51,957
15	1	190,533	53,181

Table 4. Stress values generated in the bone in the ball attachment model with different occlusal plane and collar heights by unilateral and bilateral loading.

Occlusal plane height (mm)	Collar height (mm)	Distal side force (MPa)		Mesial side force (MPa)		Maximum force (MPa)	
		Unilateral	Bilateral	Unilateral	Bilateral	Unilateral	Bilateral
9	1	5.249	2.811	4.224	0.870	5.249	3.263
12	1	4.695	2.557	3.685	0.754	4.695	3.365
15	1	4.438	2.455	3.407	0.726	4.438	3.428
15	2	4.920	2.429	3.863	0.722	4.920	3.443
15	3	5.357	2.493	4.262	0.751	5.357	3.439

Table 5. Stress values generated in the bone in the Locator attachment models with different occlusal plane heights by unilateral and bilateral loading.

Occlusal plane height (mm)	Cuff height (mm)	Distal side force (MPa)		Mesial side force (MPa)		Maximum force (MPa)	
		Unilateral	Bilateral	Unilateral	Bilateral	Unilateral	Bilateral
9	1	6.147	3.914	4.143	1.063	6.147	3.914
12	1	5.702	3.450	3.823	1.008	5.702	3.450
15	1	5.378	3.103	3.606	0.855	5.378	3.422

Stress analysis was performed using FEA software (ABAQUS version 6.11, Abaqus, Inc.). Linear static analysis was used in this study. Arbitrary 150 N vertical unilateral and bilateral loads representing the masticatory force were applied to the central occlusal fossa of the first molar of the prosthesis.[26] Mechancial properties for the prosthesis and all implant parts and bone are shown in Table 1.[13,27-30] The number of elements and nodes are summarized in Tables 2 and 3.

Results

Maximum stress values on the bone in the bilateral and unilateral loading models of ball attachment and Locator systems are shown in Tables 4 and 5.

Maximum stresses were found in the Locator model with 1 mm cuff height and 9 mm occlusal plane height. The stresses were 6.147 and 3.914 MPa in unilateral and bilateral loading conditions, respectively.

In the ball attachment models, maximum stress values of bone were observed mostly in the distal bone adjacent to the

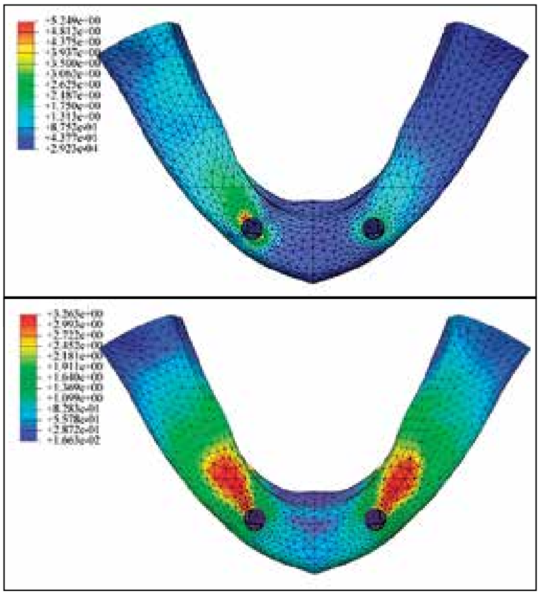

Fig. 4. Stress distribution pattern in ball attachment model when load applied. *Top.* Unilateral. *Bottom.* Bilateral.[24]

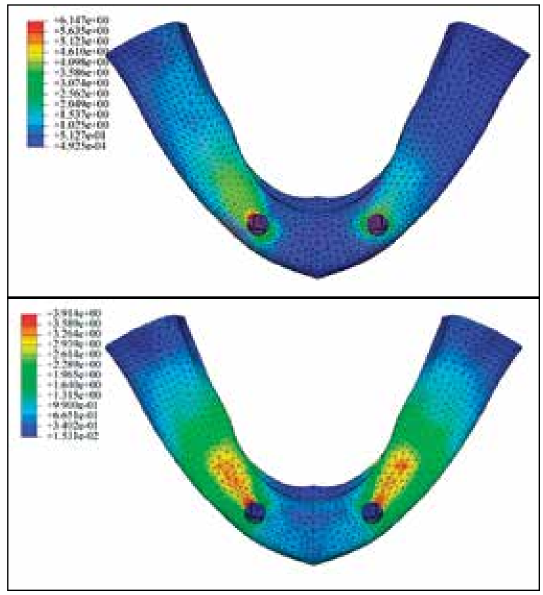

Fig. 5. Stress distribution pattern in Locator attachment model when load is applied. *Top.* Unilateral. *Bottom.* Bilateral.[24]

ipsilateral implant when a unilateral load was applied, and more distal to the bone adjacent to the implants when a bilateral load was applied (Fig. 4).

The maximum stresses in the Locator attachment system were observed in the distal side of the ipsilateral implant when unilateral and bilateral loads were applied (Fig. 5).[24]

Discussion

Dependent and independent attachment systems have been used in implant-supported overdentures. Many researchers have evaluated either ball or bar-clip attachment systems in overdentures.[8,31-34] The present study evaluated stress distributions of an overdenture retained by either a ball attachment or Locator system on 2 implants in a mandibular jaw model. Various occlusal plane heights were studied in these models.

The selection and application of different attachment systems for implant overdentures depend on many factors, such as retention, stress, restorative space, and maintenance.[3,20] Fractures of implants, attachments and prostheses can occur due to biomechanical stresses. Misch showed how stress management in implant prostheses is important in order to reduce fracture rates.[35]

Comparisons of ball attachment vs bar-clip attachments have been conducted in other studies with varying results in terms of retention and maintenance.[36,37] Kleis et al reported a higher rate of maintenance for Locator systems in comparison to ball attachments in mandibular 2-implant overdentures.[38]

Cakarer et al reported no difference between ball attachment and Locator systems regarding implant failure, replacement of attachments, and fracture of overdentures.[11] However, they found that overall, the Locator system had more advantages than the ball or bar-clip systems.[11] Celik & Uludag used a photoelastic model to evaluate the stress transfer of various types of attachments in a mandibular implant overdenture.[39] They reported that the Locator system showed greater stresses as compared to ball, bar-clip, and bar-ball attachment systems.[39] Kenney & Richards reported less stress was transferred to implants by a ball/O-ring attachment system than a bar-clip attachment.[40] Tokuhisa et al compared the transferred stresses of O-ring/ball and bar-clip attachment systems and concluded that, the ball/O-ring system minimized the stress transferred to the bone surrounding implant-supported overdentures in comparison to the bar-clip system.[3]

Maximum stresses of ball and Locator attachments in unilateral loading models in this study were 4.438 and 5.378 MPa, respectively; and in bilateral loading conditions, the maximum stresses were 3.428 and 3.422 MPa, respectively. Ebadian et al found the maximum stresses of a bar-clip attachment system model—with 1 mm bar height and 15 mm occlusal plane height—were 4.753 and 3.482 MPa in unilateral and bilateral loading conditions, respectively.[24] Comparing the result of these 2 studies showed that the Locator attachment transferred more stress than the bar clip, and the ball attachment transferred the least stress of all 3 attachment systems when a unilateral load was applied. In bilateral loading conditions, all 3 attachments transferred almost the same stress to the peri-implant bone.[24] These findings are in agreement with previous studies that used unilateral loading.[3,39,40]

In the current study, the maximum stress was found in bone adjacent to the implant in unilateral loading models; however, in bilateral loading conditions, the maximum stress of the ball attachment was observed more distal from the bone adjacent to the implant than the Locator attachment. This may be due to the more rigid behavior of a Locator system, which restricts the movement of the overdenture and thus increases the stress in the bone around the implant while decreasing the stress in the posterior residual ridge. The maximum stress locations in these models were similar to the study by Ebadian et al which evaluated bar-clip attachments of mandibular overdentures.[24] It is evident in Figures 4 and 5 that the stress distribution in the ball attachment model was more uniform than that of the Locator model, which was concentrated around the implants.

The stress obtained from applying a mastication load both unilaterally and bilaterally is distributed into 2 segments: the posterior ridge and the bone around the implants, both of which are influenced by the retention mechanism of the attachment system. Therefore, whenever the attachment system is more resilient, the stress in the bone around the implant is subsequently lessened and a part of the stress is transferred to the posterior ridge; this results in better stress distribution and thus reduces the maximum stress level. The ball attachment is more resilient than the Locator system, thus it causes more uniform and less maximum stress. Resiliency in these 2 attachment systems is closely related to the plastic caps that are used. Therefore, because the plastic volume in the cap of a ball attachment is greater than the plastic volume in a Locator attachment, and because the ball attachment has a single retention mechanism while the Locator has dual retention, the ball attachment is more resilient and transfers less stress than the Locator system.

Takeshita et al reported that the retentive forces of an attachment system affect stresses generated in the peri-implant bone during loading.[41] This finding could explain why more stresses are generated in the bone by the Locator attachment in comparison with the ball attachment. The Locator system used in this study has a dual retention mechanism, therefore it is more retentive than the ball attachment. Chen et al observed that the least retentive attachments offer greater rotation than the more retentive ones.[10] The authors compared Locator, ERA, and O-ring systems and reported that the O-ring system was the least retentive system.[10] Their findings are in agreement with the present study.

A meta-analyses study on mandibular overdentures by Cehreli et al reported no differences in marginal bone loss around implants in various attachment designs.[42] The level of stress correlated to bone resorption has not been clearly defined in the literature.[43] Since an FEA can only produce theoretical conclusions, the aim of this study was not to report absolute values of stresses but to compare stress values between different models.[28,44] It is very important to choose the appropriate attachment system according to patient characterization in terms of bone quality and quantity, stress conditions, desired retention and stability, available restorative space, and patient maintenance.

By increasing the occlusal plane height in this study from 9 to 15 mm, the maximum stress in the bone around the implant was decreased in the unilateral and bilateral loading models of the ball attachment and Locator systems, but the maximum stress in the posterior residual ridge was slightly increased in the bilateral loading models of ball attachments, which tolerated the maximum stress in these models. The study by Ebadian et al on bar-clip attachments showed the same results when a unilateral load was applied—the stress with a bilateral load slightly decreased when the occlusal plane height was increased.[24]

By increasing the collar height of the ball abutment from 1 to 3 mm, the maximum stress was increased. This was also in agreement with the study by Ebadian et al.[24] Therefore, it can be concluded that by increasing the first lever arm (distance from crest of bone to attachment level), stresses in the bone around the implants increase. By increasing the second lever arm (distance of occlusal plane of denture to attachment), the stress values were decreased in both the Locator and ball-attachment systems.

According to Cehreli et al, when severe vertical bone loss is present, vertically cantilevered occlusal loading will increase.[42] However, the results of the present study are not in agreement with that claim. This study found that increasing the occlusal plane height decreased the stress generated in bone, especially with the Locator attachment system. Increasing the collar height of abutment, or decreasing the second lever arm could result in increased stress. So it could be concluded that in abundant vertical space, even low height attachments are biomechanically advantageous.

It has been recommended that a minimum of approximately 12 mm vertical restorative space is necessary to consider a mandibular implant-supported overdenture.[45,46] The minimum space required for an implant-retained overdenture with a Locator system is 8.5 mm (vertical) x 9 mm (horizontal).[47] Based on the authors' findings and from a biomechanical and stress-generated aspect, in a restricted vertical space, ball attachments with minimum collar heights are preferred to Locator attachments.

The roles of crown/implant ratio and CHS in fixed-implant prostheses are controversial in the literature.[48-50] The role of CHS and its biomechanical effect is related to lever mechanics.[51] A CHS ≥15 mm can be biomechanically unfavorable, resulting in increased stress at the bone around the implant.[52] It appears that the CHS role in fixed-implant prostheses is not completely applicable in implant overdentures. Our findings indicate that by increasing the CHS (via occlusal plane height), the stress generated in the bone was decreased. This may be related to the different support, movement, and leverage mechanisms of the 2 tested prostheses.

There are some unavoidable limitations in an FEA study, mainly in biologic simulations, which compelled the authors to assume some simplifications. Bone is a complex living structure without a defined pattern; its characteristics vary among individuals, and its actual mechanical properties are not precisely established. Furthermore, the use of FEA in a study of an extremely accurate anatomy of a bone structure may limit the results to that particular structure. As such, certain simplifications were adopted in this study to generalize the results and facilitate the study without compromising the validity of the findings. The implants were modeled without threads, as the aim of the study was to analyze the stresses on implants and not the mechanical interactions within the bone.[28] It has been said that this assumption results in an underestimation of stress patterns in bone, as reported in previous studies.[53,54] In addition, the connecting screws at the implant-abutment interface were not modeled, although some studies have shown that modeling the screw is not necessary.[28] It was assumed that the models were homogenous and isotropic. Because this study was comparative in nature, such assumptions would not interfere in the results, since they were present in all models.[55]

Conclusion

Within the limitation of this study, it can be concluded that by decreasing the first lever arm (distance from crestal bone to abutment) in unsplinted resilient attachments in a mandibular implant overdenture, the stresses generated in bone are decreased. Also, by increasing the second lever arm (distance from occlusal plane to abutment), the stresses in bone were decreased. Finally, this study found that Locator attachments could generate more stresses than ball attachments in the same CHS.

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