Mandibular 2-implant-supported overdentures (IODs) consist of 2 anterior mandibular implants and attachments that support a complete denture. The IOD has become a widely used treatment for the rehabilitation of patients with edentulism and is recommended as the first choice treatment because of its clinical effectiveness in improving masticatory performance and patient satisfaction.1-3

When masticatory load is exerted on an IOD, the prosthesis can rotate around the implants as a fulcrum.4 The amount of rotation depends on both the attachment system and the geometric anatomy of the residual ridge.5,6 Several in vivo,7 ex vivo,8 and in vitro9-12 studies have reported that the applied load is concentrated on the anterior implants during function. Therefore, most dentists provide maintenance for the anterior implants. This helps to reduce cantilever effects by attempting to retain patients’ mucosal support through denture relining. However, every patient exhibits different residual ridge resorption rates, applies different occlusal forces, and has different masticatory habits; furthermore, not all patients follow maintenance programs. Nevertheless, with respect to IOD

ABSTRACT

Statement of problem. Progressive resorption of the posterior residual ridge and attachment wear increase the rotational movement of mandibular 2-implant-supported overdentures (IODs). Limited information is available regarding the biomechanical effects of rotational movement on anterior implants during mastication.

Purpose. The purpose of this in vitro investigation was to analyze the effects of posterior ridge resorption and attachment wear, using simulated IODs to examine periimplant strain changes under dynamic loading conditions.

Material and methods. Two dental implants were positioned in the canine regions of a mandibular edentulous cast. Two mandibular edentulous models were fabricated from the cast by using a fixture-level impression technique, and IODs reinforced with a cobalt-chromium cast framework were prepared using the laboratory models. Two different types of stud attachments (Locator and O-ring) were connected to each paired model and to the IOD. Using a dynamic load of 100 N, continuous stress-strain changes were recorded under 3 conditions: the original condition of the paired laboratory models and the IODs, following a 1-mm reduction of the posterior residual ridge support, and after performing a fatigue test to simulate attachment wear after reduction of the posterior ridge support. After these measurements, a scanning electron microscope (SEM) was used to analyze attachment wear.

Results. In all implants, the 1-mm posterior ridge reduction and attachment wear procedure did not remarkably elevate tensile forces compared with their original condition. All stress-strain curves showed phased strain changes caused by the rotational movement of the IODs. After the fatigue test, the shape of the stress-strain curve changed from a smooth curve to a polygonal line compared with that in the previous records. The Locator matrices showed more wear than the other attachment components.

Conclusions. Neither attachment wear nor an increase of the IOD rotational movement caused by an approximately 1-mm decrease in the posterior mucosal support led to significant changes in the periimplant strain in IODs. (J Prosthet Dent 2015;114:839-847)
Clinical Implications

Implant-supported overdentures (IODs) with Locator and O-ring model attachments may be safely used in patients showing stable residual ridge resorption. However, in patients who have recently become edentulous, clinicians should consider the factors of rapid residual ridge resorption and freedom of rotation in the attachment system. Regular recall and relining of these IODs could reduce periimplant strain and attachment wear.

complications, patients more frequently reported technical issues, such as retention loss and abutment screw loosening, rather than biological issues. Clinical studies have also reported the successful maintenance of marginal bone heights for implants, as long-term implant survival rates, in IOD wearers.

Biomechanically, progressive residual ridge resorption and attachment wear can increase the rotational movements of IODs; this functional movement during mastication may influence periimplant stress distribution. Jacobs et al reported increased posterior ridge resorption over the same period in IOD patients with a short edentulous period compared with that in patients with a complete denture. Wright et al reported posterior ridge resorption of 0.5 mm over 5 years, whereas Kordatzis et al reported 0.69 to 1 mm of resorption over the same period. Through prospective studies spanning 10 years, de Jong et al reported vertical posterior bone loss of 1.44 mm and Raedel et al of 1.5 mm. Moreover, the attachment system of the IOD, which serves as an element of retention, stability, and support, exhibits wear accompanied by the deformation and deterioration of the matrix and patrix. Although the mechanism of wear for different attachment systems is not fully understood, several factors, including the repeated insertion and removal of IOD, cyclic loading on the denture, and the oral mecanochemical environment, can contribute to attachment wear. However, the biomechanical influences of increased rotational IOD movement on anterior implants have not yet been explored.

In implant dentistry, stress-strain analysis and stress distribution analysis using photoelastic have been used to investigate the biomechanical relationships between load and periimplant stress. Photoelastic models and finite element models, however, have examined stress distribution under static loads. Therefore, the results from use of photoelastic models and finite element analyses are difficult to apply to dynamic load assays. To investigate the influences of increased rotational movements of IODs on implants during mastication, the present study used a qualitative analysis of stress-strain changes under dynamic loading conditions. The purpose was to investigate the effects of posterior ridge resorption and attachment wear on periimplant strain during the functional movements of IODs. The hypothesis of this study was that the increased rotational movements of IODs raise the periimplant strain, especially the tensile forces, and affect the changing patterns of stress-strain curves.

MATERIAL AND METHODS

Two pairs of mandibular completely edentulous polyurethane models with implants in the canine regions and their laboratory IOD were fabricated. Locator (Zest Anchors) and O-ring (Osstem Implant Co) attachments were attached to each pair of models and IOD (Locator model no. 1 and O-ring model no. 1), and a strain gauge (SG) (resistance: 350.0 ±0.2% ohm; gauge factor: 2.10% ±1.0%; gauge length: 0.79 mm; product no. EA-06-031CE-350; Vishay Micromeasurements Group) was located to the labial surface adjacent to the implant. Measurements of stress-strain changes were carried out under dynamic loading from 0 to 100 N for each loading. Stress-strain measurements were recorded at 3 time points according to the given conditions. The first time point was pretreatment (PT), indicating the measurement was done under the original conditions of the experimental models and the IODs. At the second time point, the stress-strain changes were recorded after reduction (AR) of the posterior ridge support from the original condition. The final stress-strain measurement was performed after a fatigue test (AF) to simulate attachment wear on the previous models and on the IODs of the AR. At each time point, we carried out 3 stress-strain measurements. Stress-strain changes and average strain values of each measurement time point were compared, and effects of each variable were analyzed.

Experimental model and IOD fabrication

The laboratory analogs of an internal connection-type implant (3.5×10 mm; TS II; Osstem Implant Co) were located to leave gaps of 20 mm in both canine regions of a completely edentulous mandibular cast copied from an edentulous dental model (Nissin Dental Products Inc). The impression copings were connected and duplicated with a silicone mold (Silastic 3481; Dow Corning). The implant fixtures were connected to the impression copings that were embedded in the silicone mold. Water-resistant polyurethane (Exakto-form; Bredent) was poured into the mold to obtain tight and even contact between the implants and the polyurethane matrix. A second set of polyurethane experimental models was fabricated using the same procedure. Locator (Zest Anchors) abutments were connected to one of the experimental models and O-ring (Osstem Implant Co)
abutments to the other model at a torque of 35 Ncm (Fig. 1A). Experimental IODs were completed after a cobalt-chromium framework was fabricated by the refractory cast method. An attachment matrix was affixed to each IOD matrix to form a pair. A standard blue (retentive force: 6.7 N) was used for the Locator nylon matrix. To simulate the nonlinear behavior of mucosa under mechanical loading, the surface of the experimental model was uniformly reduced by 2 mm. The IOD was then placed in its original position, and a silicone impression material (Examix fine light body; GC Corp) was used to fill the space between the inner surface of the IOD and the removed surface of the model. In order to apply load onto the IOD in such a way that the load could be simultaneously transferred to both the left and the right molar regions, an aluminum occlusal jig with a 2-mm thickness was affixed to the IOD with pattern resin (GC Corp). To ensure that the load was applied to the same point during each stress-strain measurement, a reference line was engraved on the occlusal jig. The loading point was the extended line between the left and right first molars in the experimental model and at the medial line points of the intersection (Fig. 1B).

**STRAIN GAUGE PLACEMENT**

The SG (resistance: 350.0 ± 0.2% ohm; gauge factor: 2.10% ± 1.0%; gauge length: 0.79 mm; product no. EA-06-031CE-350; Vishay Micromeasurements Group) was made of an electroresistant material. When it was connected to the Wheatstone bridge circuit (SoMat eDAQ; HBM), which transmitted resistance changes as voltage changes, external force-induced changes in the length of the resistance wire within the SG were converted to strain. In a linear SG, a positive (+) value indicated tensile force and a negative (−) value compressive force.

Simulation mucosa on the areas planned for SG placement was cut out to avoid pressure from the prosthesis. The SG was placed parallel to the long axis of the implant in the crestal area of the labial surface, adjacent to the implant, which corresponded to the resistance side of the lower posterior rotational movement of the prosthesis (Fig. 1C). This was done because the cortical bone, which surrounds the implant, has properties that are more vulnerable to tensile or shear forces than to compressive forces. In addition, the site of SG placement was determined on the basis of an earlier study, which found that the load applied to implants was distributed mainly in the crestal area. After placement, to eliminate any effects from the water immersion environment, the SG and the conducting wires were water proofed. Depending on the type of attachment and location of the implant, SG is hereafter referred to as SG L1 or L2 for the Locator model and SG O3 or O4 for the O-ring model. SG L1 and SG L2 refer to right and left implant sites, respectively, of the Locator model, and SG O3 and SG O4 refer to the right and left implant sites, respectively, of the O-ring model.
Stress-strain measurement

After the Wheatstone bridge circuit was connected to each SG, compressive dynamic loads up to 100 N were applied 3 times sequentially for each of the 3 different conditions: PT (before the test conditions were applied), AR (after the reduction of the posterior ridge support to simulate posterior ridge resorption), and AF (after the fatigue test to simulate attachment wear). The fatigue test was applied in the presence of posterior ridge resorption.

The IODs equipped with the Locator and the O-ring polyurethane models were fixed to a Universal Testing Machine (model 3366; Instron), and the axial load was increased up to 100 N (crosshead speed: 1 mm/min) while changes were measured in the periimplant strain (Fig. 2A). The magnitude of load simulated a moderate level of masticatory force in patients with maxillary complete dentures and mandibular IODs.31,32 After each measurement, a waiting period was observed to allow the strain value to return to zero before the next measurement was made.

With regard to the amount of posterior ridge resorption, 1 mm of material from the inner surface of the denture was uniformly removed in accordance with studies that reported amounts of long-term ridge resorption in patients with mandibular IODs.21-23

For the fatigue test, cyclic loading and repeated insertion-removal cycles were simulated. A mastication simulator (CS-4; SD Mechatronik GmbH) was used for cyclic load testing, with a 50-N vertical load applied to the loading point of the occlusal jig at a speed of 40 mm/s, and a Z-axis movement of 2 mm for 300,000 cycles. In addition to cyclic loading, thermocycling (5°C-55°C) was simultaneously conducted in a water immersion environment (Fig. 2B). After cyclic loading was completed, 1500 insertion-removal cycles were made. This number of insertion-removal cycles was assumed to simulate 1 year of IOD usage, meaning it would be inserted and removed 4 to 5 times daily.

Scanning electron microscopy (SEM) (Nova Non-oSEM200; FEI) was used to observe changes on the attachment surfaces after the fatigue test. SEM images were obtained at 10 kV of electron acceleration voltage.

Strain values in the mandible were estimated using the linear regression equation of the stress-strain curve that showed the largest slope and maximum strain value. The maximum occlusal force of maxillary complete denture and mandibular IOD wearers was assumed to be 150 N,31,32 and by converting the modulus of the polyurethane model and mandibular vertical components as proportionality, the strain value expected on the labial surface of the implant on application of the maximum occlusal force was calculated. The modulus of the polyurethane model, as indicated in the product information provided by the manufacturer, was 3.9 GPa, whereas the modulus of the mandible that exhibits 3-dimensional anisotropic deformation on load application was calculated as 11 GPa, considering only vertical components. The modulus of the mandible was set to 11 GPa, which corresponded to the average value of 8.2 GPa reported by Arends and Sigolotto33, 34 and of 13.8 GPa reported by Dechow et al.35

RESULTS

Stress-strain curves are presented in Figure 3 and average value changes for each condition in Table 1. In interpreting strain value and strain change, positive readings indicated tensile forces, and negative readings indicated compressive forces. SG L1 and L2 values were measured using the Locator model (Fig. 3A, B), and SG O3 and O4 were measured using the O-ring model (Fig. 3C, D). The stress–strain curve differed depending on the attachment system, the implant location within the model, and the testing condition.

In terms of the attachment system, a wide range of variation in the Locator model was observed. In particular, SG L1 showed a maximum strain variation of 170
\[ \mu \varepsilon \text{, depending on the changes in testing conditions. The maximum tensile forces were also larger in the Locator model than in the O-ring model.} \]

With regard to the pattern of changes based on the measurement time points, the Locator model showed more sensitive responses to changes under testing conditions. A tensile force was observed on the labial surface of all implants in the PT condition. In the AR condition, the compressive force increased in both the SG L1 and SG O4 and showed slight rises in the tensile force for both the SG L2 and SG O3, with a curve similar to that for the PT condition. In the stress-strain curve for the AF condition, SG L2 and O3 showed curves similar to those for the AR condition, whereas SG L1 and O4 showed an increase in tensile forces, unlike that in the AR condition. Moreover, all previously smooth stress-strain curves changed to polygonal line forms with the AF condition.

As the load increased, similar patterns were observed in all stress-strain curves. It was possible to classify these similar patterns into 3 phases: an initial increase in tensile force (phase I); an increase in tensile and compressive forces according to the attachment system (phase II), and relatively steady maintenance of strain (phase III) (Fig. 3).

In the SEM images of the attachment surfaces after the fatigue test, adhesive wear and abrasive wear of the matrix appeared, although no changes were observed in the patrix (Fig. 4). Changes in the nylon matrix of the
Locator were particularly prominent; in addition, deformation of the center post was clear.

With the maximum occlusal force assumed to be 150 N, 752.13 με was obtained as the strain value when calculated using the linear regression equation from SG L2, which showed the largest slope and maximum tensile strain value (Fig. 5).

**DISCUSSION**

The present study used simulated IODs to investigate the effects of posterior ridge resorption and attachment wear on periimplant strain under dynamic loading conditions. A qualitative analysis approach was used to investigate how the increased rotational movement of IODs due to changes in posterior mucosal support and in attachment wear affects the stress-strain changes in anterior implants. Results indicated that uniform reduction of the posterior support by 1 mm and the fatigue test affected periimplant strain variations; however, the tensile forces showed no significant increases. This finding supported the results of a previous study, which reported that when stud-type attachments were used, the applied load was relieved by the resilient matrix, connector for the abutment head, and deformation of the denture.9 Furthermore, an increase in rotational movement of the IOD within the permissible range allowed by the attachment system did not significantly increase the periimplant strain. In terms of IOD rotation, Chen et al6 reported that the IOD rotation allowed by a resilient-type attachment occurred at a minimum distance of 1.4 mm from the distal end of the denture and was at least 2.0 to 11.8 degrees, depending on the attachment type and retentive force. Although the study by Chen et al6 did not examine attachment wear, their resulting values were similar to or greater than the amount of posterior ridge resorption in patients22,23 who had been wearing IODs for 10 years. In the present study, a consistent influence of attachment wear on changes in the periimplant strain was observed from the shape of the stress-strain curve, and after the fatigue test, all stress-strain curves were observed to change from a smooth shape to a polygonal line shape.

Table 1. Periimplant strain values

<table>
<thead>
<tr>
<th>Strain Gauge</th>
<th>Measurement Time</th>
<th>Range of Strain Values (με)</th>
<th>Relative Change of Peak (+) Strain Value Compared With PT (με)</th>
<th>Variation Width of Strain (με)</th>
<th>Width Change by Measurement Time (με)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG L1 PT</td>
<td>0-82.24</td>
<td>-30.3</td>
<td>82.24</td>
<td>31.14</td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>-61.44 to 51.94</td>
<td>26.94</td>
<td>113.38</td>
<td>-4.2</td>
<td></td>
</tr>
<tr>
<td>AF</td>
<td>0-109.18</td>
<td></td>
<td>109.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG L2 PT</td>
<td>0-149.61</td>
<td>14.23</td>
<td>149.61</td>
<td>14.23</td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>0-163.84</td>
<td>-12.7</td>
<td>163.84</td>
<td>-26.93</td>
<td></td>
</tr>
<tr>
<td>AF</td>
<td>0-136.91</td>
<td></td>
<td>136.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG O3 PT</td>
<td>-1.24 to 15.26</td>
<td>33.76</td>
<td>49.02</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>0-49.02</td>
<td>33</td>
<td>49.02</td>
<td>-0.76</td>
<td></td>
</tr>
<tr>
<td>AF</td>
<td>0-48.26</td>
<td></td>
<td>48.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG O4 PT</td>
<td>0-24.66</td>
<td>-21.45</td>
<td>24.66</td>
<td>-14.02</td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>-7.43 to 3.21</td>
<td>-11.13</td>
<td>10.64</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>AF</td>
<td>-2.71 to 13.53</td>
<td></td>
<td>16.24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AF, after fatigue test; AR, after reduction of posterior ridge support; PT, pretreatment; SG, strain gauge.

With regard to the pattern of change in the periimplant strain according to the type of attachment, the Locator showed significant variations depending on the testing conditions. This could be attributed to differences in the retention and housing design of the Locator and O-ring systems (Fig. 1A). The center post and external wall of the Locator matrix acted as a resistance factor for IOD rotation, and the metal housing surrounding the matrix enabled the force from the IOD to be continuously transferred to the implant. The rubber ring in the O-ring system is located inferiorly in the undercut of the matrix to provide retention, and as long as the metal housing and matrix do not come in direct contact, the load is dispersed to the ridge within the elastic limitations of the rubber ring.9,10 Limited information is available regarding periimplant strain changes under dynamic loads, as most studies of strain changes around implants were conducted using static loads to compare the maximum values of different attachment systems.9,25,26 Thus, it is difficult to compare our results with theirs because of the different experimental conditions. We concluded that attachment designs that allow more IOD rotation resulted in less concentrated stress on the anterior implants.

Regardless of the attachment system or test condition, similar patterns of change with an association between rotational movement of the IOD and the periimplant strain were observed in all stress-strain curves (Fig. 3). Phase I, in which the initial tensile force increases, is interpreted as the joining process between the matrix and the rubber ring, whereas phase II, in which the IOD sinks...
Figure 4. Scanning electron microscopy (SEM) images of patrices and matrices of Locator and O-ring systems after fatigue test. A, B, ×29 and ×100 magnification, respectively, of Locator patrix. C, D, ×28 and ×100 magnification, respectively, of Locator nylon matrix. E, F, ×28 and ×100 magnification, respectively, of O-ring patrix. G, H, ×28 and ×100 magnification, respectively, of O-ring rubber matrix.
after the matrix is completely seated, is interpreted as the phase with various patterns based on the attachment’s design and elasticity and mucosal thickness and elasticity. Phase III, in which the strain is maintained with relatively consistent values, is the phase in which the attachment’s elasticity and mucosal displacement are exceeded; therefore, it is viewed as the phase in which the load increases while the rotational movement of the denture stops at the end point. However, unlike the measurements obtained when the mandibular model was firmly fixed on a flat surface, the actual mandible would be expected to show strain variations different from those in phase (III) because of mandibular torsion.

In the present study, because a strain experiment on a human participant was ethically impossible, the strain that would be created on the mandibular labial surface was estimated after assuming a maximum occlusal force of 150 N in a maxillary complete denture and patients with a mandibular IOD. The strain value obtained by using the linear regression equation for SG L2, which showed the largest slope and maximum tensile strain value, was 752.13 με. Frost indicated that strain is generated in the bone cells from the stress exerted on the bone and that, depending on the degree of deformation, an increase in bone density or fatigue failure can occur. Furthermore, the range of bone deformation under a general load corresponded to 50 to 1500 με. Although the value calculated using the regression equation for SG L2 falls within the bone deformation range of 50 to 1500 με under a general load, it is expected to be different from that for actual teeth when the tendency of the mandible to show anisotropic deformation under an applied stress is taken into consideration. Because of the nature of the strain experiment, which showed significant differences depending on experimental conditions, comparison of the strain values may be unreasonable. However, according to a study that connected a stud attachment to an implant placed in the mandible of a human cadaver and applied a static load of 100 N to the IOD to measure the strain in the labial surface of the implant, an average of −463 to −777 με was measured from the implant’s labial surface ridge, depending on the loading point. Because a ball and metal socket attachment was used in that particular study and the strain was measured in a cadaver, the decreased elasticity of the mucosa may have been an influencing factor for the (−) measurement value.

The present study has limitations. The attachment wear and residual ridge resorption factors could not completely replicate clinical situations, and simple comparisons using SGs were difficult, as SG measurements are sensitive to testing conditions. Even though the same SGs were placed in the same locations, standardizing the results between the different models was difficult. Moreover, this study aimed to analyze the changes of strain under dynamic loading conditions by simulating the rotational movement of IODs, and that was why we limited the number of models for each set-up. However, we feel the results of this in vitro study are significant because we attempted to investigate the effects of ridge resorption and attachment wear on periimplant strain in mandibular IODs. Our results suggested clinical implications that when a resilient attachment system is used, such as Locator and O-ring, a slight posterior ridge resorption and attachment wear may not cause a significant increase in periimplant strain. From a clinical perspective, these results may serve as experimental evidence for maintaining the marginal bone height for implants and long-term implant survival rates in mandibular IOD wearers. However, for patients who have recently become edentulous, during which extensive posterior ridge resorption occurs, the decrease in posterior mucosal support would have a larger influence on tension distribution around the implant. Even though the results of this in vitro study did not indicate considerable biomechanical effects on the implants, regular recall and relining of IODs could reduce periimplant strain and attachment wear. Furthermore, because increased masticatory performance in patients with IODs may accelerate ridge resorption, careful assessments of changes in mucosal support for IOD wearers who show frequent retention loss may also be required.

To know the effects of the increased rotational movement on IOD derived from posterior ridge resorption and attachment wear on the anterior implants, further clinical studies are needed to investigate the effects over various time periods. Because of the ethical limitations in conducting stress-strain analyses in live patients, a finite element analysis combined with 3D rendering using cone-beam computed tomography seems to be an appropriate model for clinical research.

Figure 5. Linear regression equation for strain gauge (SG) L2 after reduction of posterior ridge support (AR).

\[ y = 1.682x + 14.364 \]
CONCLUSIONS

The conclusions derived from the results of the present study are as follows:

1. The pattern of changes in stress around the implant during functional movements of the mandibular IOD varied according to attachment type.
2. When the Locator and O-ring attachments were used, approximately 1 mm of vertical posterior ridge resorption and attachment wear did not affect the increase in strain on the labial surface area of the implant.
3. Attachment wear affected the transfer of stress from the IOD to the implant, which also affected the shape of the stress-strain curve.
4. Among the attachment components used in the experiment, the Locator matrix showed the largest deformation during the fatigue test, which affected the strain variations based on an increased load.

REFERENCES