Mechanical Study of Optimal Implant Position for Maxillary Implant-Supported Overdentures Using Three-Dimensional Simulation Software

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Purpose: The purpose of this study was to determine the optimal positioning of implants for maxillary implant-supported overdentures (MIODs) using finite element analysis (FEA).

Materials and Methods: Three-dimensional (3D) finite element models were built incorporating the maxilla, mucous membrane, removable denture, and artificial teeth using FEA software. Four models were prepared: one without an implant; one with two implants in the region of the lateral incisor; one with two implants in the first premolar region; and one with four implants in the lateral incisor and first premolar regions. Occlusal load was applied to the model, and denture displacement and the distribution of stress in the surrounding bone and mucous membrane were observed and measured. Results: The maximum equivalent stresses to the bone and mucous membrane were highest in the premolar and anterior areas, respectively. Stress to the bone was concentrated around the implants, whereas stress in the mucous membrane was concentrated along the posterior margin. Denture displacement in the anterior direction was highest in the model without implants, while denture displacement in the posterior direction was less affected by the presence of implants. Overall, denture displacement in the four-implant model was smaller than that in the other models. Implant angle affected the stress distribution, with highest stress to the bone when the implant was positioned in a palatal direction and highest stress to the mucous membrane when placed mesially. However, implant angle had little impact on denture displacement, with almost the same stress for implants at all tested angles. Conclusion: Optimal implant position can stabilize overdentures and reduce stress to the bone and mucous membrane. Stress is reduced when implants are inserted in the premolar area and when the direction of the implant is perpendicular to the occlusal plane. Int J Prosthodont 2018;31:619–626. doi: 10.11607/ijp.5759

Implants have been widely used as a reliable option for the treatment of a range of dental concerns. However, many reports have shown low survival and success rates of implants in the maxilla compared to those in the mandible. It is speculated that this may be because the bone quality and quantity in the maxilla are reduced compared to that in the mandible. However, patients will continue to require treatment because of tooth loss in the maxillary region. The purpose of this study was to find the optimal implant position in the maxilla using implant simulation software and clinical anatomical morphology data obtained using computed tomography (CT).

In a previous study by the present authors, it was found that the premolar region is the most favored area in the maxillary arch for implant placement in terms of bone height, width, angulation, and quality. In this experiment, four options for implant positioning were tested using three-dimensional (3D) modeling: no implant; two implants in the lateral incisor area; two implants in the premolar area; and four implants in both areas. The number of implants and the implant positions were then compared using stress distribution and denture displacement measurements.
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Materials and Methods

Three-Dimensional Model

A commercially available maxillary model (G9-AH.01, Nissin Dental Products) including the complete maxilla, mucous membrane, and removable denture was scanned using CT, and the Digital Imaging and Communications in Medicine (DICOM) data were used to build a 3D finite element model including the maxilla, mucous membranes, removable denture, and artificial teeth. The model was built using finite element analysis (FEA) software (Mechanical Finder version 6.1, extended edition; Research Center for Computational Mechanics) (Fig 1).

Four types of the model were prepared: one with no implants; one with two implants in the lateral incisor area; one with two implants in the first premolar area; and one with four implants, two each in the lateral incisor and first premolar areas (Fig 2). The diameter of the implants was 3.75 mm, and the length was 8 mm. The implants were cylindrical with no thread (for efficiency of the analysis). The platform of the implant was placed at the same height as the bone ridge. Anterior implants were inserted at an angle that bisected the palatal and labial bones, whereas premolar implants were inserted perpendicular to the occlusal plane. To compare the influence of implant angle in the premolar model, five different implant angles were used to set the premolar implant (Fig 3). The dome-shaped top of the abutment was 2 mm higher than the mucous ridge.

Contact conditions were set as “gap” to allow for sliding and separation between the implant and denture and between the denture and mucous membrane and as “bond” to prohibit sliding and separation in other borders.

Material Properties

The material properties, including Young modulus and Poisson ratio, were set according to previous studies4–6 (Table 1).

Loading and Constraint Conditions

A vertical load of 49 N was applied to the second premolar, first molar, and second molar positions of the occlusal surface. The upper surface of the maxillary bone was constrained (Fig 4). The model surface was a triangular shell element, and the interior of the model was a solid element. The total number of nodes was 57,591 to 59,479; of shell elements was 15,286 to 15,334; and of solid elements was 282,260 to 292,533.

Finite Element Analysis

After preparation of the model, linear analyses were performed using 3D FEA software (Mechanical Finder, 6.2). Stress distribution to the bone around the implant and to the mucous membrane was measured, focusing on the largest equivalent stress in the concentrated area. The maximum displacements in the anterior and posterior parts of the denture were also measured.
Results

Maximum Equivalent Stress in the Bone Around the Implant

Figure 5 shows the distribution of stress in the maxilla. Stress was concentrated in the bone around the implant in each of the implant models. The maximum equivalent stress to the bone around the implant was 1.2 MPa in the anterior model, 5.1 MPa in the premolar model, and 4.9 MPa in the four-implant model. Regarding position of implant, the maximum equivalent stress in the bone around the implant in the anterior model was smaller than that in the premolar model (Fig 6). Regarding number of implants, the maximum equivalent stress in the bone around the premolar implant was larger in the two-implant premolar model than in the four-implant model (Fig 6).
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**Maximum Equivalent Stress in the Mucous Membrane**

Figure 7 shows the stress distribution to the mucous membrane in both the anterior and premolar models. Stress was concentrated along the posterior margin in the mucous membrane in both models. The maximum equivalent stress in the mucous membrane was $4.0 \times 10^{-2}$ MPa in the anterior model, $3.0 \times 10^{-2}$ MPa in the premolar model, and $1.7 \times 10^{-2}$ MPa in the four-implant model. Regarding position of implant, the maximum equivalent stress to the mucous membrane was lower for the premolar model compared to the anterior model (Fig 8). Regarding number of implants, the maximum equivalent stress was lower for the four-implant model than for the two-implant model (Fig 8).

**Maximum Denture Displacement**

Figure 9 shows the degree of denture displacement in the models without implant support, with implant support in the anterior area, and with implant support in the premolar area. In the model without implant support, anterior denture displacement was largest, whereas in the models with implant support (both anterior and premolar), posterior displacement was largest. The maximum anterior denture displacement was $1.8$ mm in the model without implant support, $0.26$ mm in the model with an anterior implant, $0.29$ mm in the model with a premolar implant, and $0.19$ mm in the four-implant model (Fig 10a). The maximum denture displacement in the models with anterior and premolar implants was about one-fifth that of the displacement in the model without implant support. Overall, denture displacement in the four-implant model was smaller than that in the other models.

The maximum denture displacement in the posterior part was $0.87$ mm in the model without implant support, $0.87$ mm in the model with an anterior implant, $0.41$ mm in the
model with a premolar implant, and 0.27 mm in the four-implant model (Fig 10b). The maximum denture displacement in the model with a premolar implant was about half that measured in the model without implant support and with an anterior implant.

**Implant Angle**

**Maximum Equivalent Stress in the Bone Around the Implant**

The maximum equivalent stress in the bone around the implant was 4.6 MPa (vertical angle), 5.3 MPa (mesial), 6.0 MPa (distal), 6.8 MPa (buccal), and 9.8 MPa (palatal) (Fig 11).

**Maximum Equivalent Stress in the Mucous Membrane**

The maximum equivalent stress in the mucous membrane was $3.0 \times 10^{-2}$ MPa (vertical angle), $3.6 \times 10^{-2}$ MPa (mesial), $1.9 \times 10^{-2}$ MPa (distal), $0.7 \times 10^{-2}$ MPa (buccal), and $0.8 \times 10^{-2}$ MPa (palatal) (Fig 12).

**Discussion**

Most articles regarding maxillary implant overdentures report low survival rates of the maxillary implant, as well as problems associated with the superstructure.\textsuperscript{7–9} Other studies have shown that high failure rates occur among subjects for whom a fixed prosthesis was planned in the maxilla.\textsuperscript{9–11} Sanna et al\textsuperscript{12} reported higher survival rates with the use of two-splinted implants for supporting the maxillary implant overdenture. Overall, it appears that implant failures occur less in patients for whom implant overdenture treatment is originally planned and when a treatment plan considers the
appropriate biomechanical parameters, including the position and number of implants and the later potential movement of the implant overdenture after insertion.

A few studies\textsuperscript{13,14} have previously reported biomechanical results regarding the number and position of implants for maxillary edentulous patients treated with implant overdentures. Therefore, in the present study, the position and number of implants were analyzed from the perspective of anatomical morphology and bone quality using 3D FEA software and patient CT data.

**Methods**

**Validation of the Model**

In this study, the residual ridge of the model was resorbed to the mean level. Figure 14 shows that the results from this model are within the range of that for 10 clinical cases from a previous study.\textsuperscript{3}
**Design of the Implant Overdenture**

Some patients request a maxillary implant overdenture without palatal coverage.\(^{15,16}\) Satisfactory results have been reported for patients treated with and without palatal coverage in maxillary implant overdentures.\(^{11,17,18}\) However, in cases where the maxillary overdenture is supported by only a few implants, palatal coverage is crucial for providing the appropriate support from the mucous membrane.

Sadowsky\(^{19}\) previously reported that at least four implants are necessary for maxillary implant overdenture stability and noted that better prognoses are obtained when using overdentures with palatal coverage. In this study, because two or four implants were used to support the overdenture, the overdenture sufficiently covered the palate.

**Results**

**Equivalent Stress in the Bone Around the Implant and in the Mucous Membrane**

Ogata et al\(^{20}\) and Ando et al\(^{21}\) previously reported that support from the mucous membrane can reduce the load to the implant. The present results showed that the bone around the anterior implant receives more stress than that around the premolar implant in the two-implant prosthesis. This is presumably because of the increased support from the mucous membrane in the anterior implant than in the premolar implant.

Tsutsumi et al\(^{22}\) reported stress ranges that affect the quality of bone: where the stress is below 40 MPa, the bone is classified as being within the safety area; between 40 MPa and 60 MPa, the bone is in the marginal area; and above 60 MPa, bone resorption is probable. In the present study, because all equivalent stresses to the bone were under the threshold of 60 MPa, there was negligible possibility of bone resorption in the model.

**Denture Displacement**

Denture displacement was reduced with implants compared to without implants and was also reduced in cases where the denture was supported by a premolar implant as opposed to an anterior implant. These findings suggest that a premolar implant can stabilize an overdenture.

**Number of Implants**

Maeda et al\(^{23}\) reported that, when more than four implants are widely distributed within the arch, the overdenture is supported only by these implants because the rotational movement around the fulcrum line is restricted. Here, it was shown that the maximum denture displacement and maximum equivalent stress in the mucous membrane were smaller when the overdenture was supported by four implants in the anterior and premolar areas than by only two premolar implants, as the maximum equivalent stress around each implant was the same. This is presumably because the overdenture can rotate around the fulcrum line between the premolars and functional force is distributed to both the implants and the mucous membrane.

A study by Damghani et al\(^{13}\) showed that, when implants are separated by more than 16 mm in the maxilla, the load from the denture base to the palatal bone is the same whether the maxillary overdenture is supported by four or eight implants. These findings also suggest that there is no difference in the maximum equivalent stress in the bone around the implant, indicating that even two implants in the premolar area can effectively stabilize the maxillary implant overdenture.

**Angle of Implant**

Some previous reports\(^{24,25}\) have shown that inclined implants receive larger lateral forces than those not inclined, while others\(^{26}\) report the clinical value of inclined implants. In the present study, the palatal implant received the largest maximum equivalent stress, and this was substantially lower in vertical implants and in implants positioned at other angles. Misch\(^{27}\) indicated that the implant angle should be smaller than 20 degrees in the direction of the force; in the present study, the angles were set within 15 degrees of the vertical implant. Because these angles were within the acceptable range of 20 degrees, there was little difference among the tested angles. Therefore, it is suggested that the implant angle should be the same as the loading direction, and, in cases where this is not possible (eg, with anatomical limitations, such as bone shape), an inclined implant is acceptable to stabilize the overdenture.

**Clinical Implications**

The primary limitation of this study was that it was a simulation study that used a model with constant properties; however, hypothetical scenarios based on these findings can be discussed. For instance, when a patient can only receive two implants because of poor quality or quantity of the maxillary bone, the premolar area should be chosen over the anterior area to stabilize the denture. However, in cases where the implant can only be inserted in the anterior area, the two implants should be connected to improve the stability of the denture. In addition, the denture should have
sufficient stiffness to control for the stress from the denture base to the mucous membrane, and surgeons should aim to reduce residual ridge resorption.

On the other hand, when an implant is lost under the fixed prosthesis and there is a need to change the prosthesis to a removable denture, it is recommended that implants in the anterior and premolar areas should be used as the first option, with preference to the premolar area on both sides. When implants can only be positioned in the anterior area, it is important to choose an overdenture attachment that can connect the two implants to avoid lateral stress, as mentioned above.

Conclusions

The results of the present 3D FEA showed that the stability of overdentures improves when implants are positioned in the premolar area and that stress to the bone around the implant is reduced when implants are inserted perpendicular to the occlusal plane. These results suggest that the premolar area is the optimal position to stabilize overdentures and that inserting the implant in the appropriate orientation helps to maintain this stability and reduce stress.

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References