All-on-4 Concept: A 3-Dimensional Finite Element Analysis

Gianpaolo Sannino, DDS, PhD

The aim of this work was to study the biomechanical behavior of an All-on-4 implant-supported prosthesis through a finite element analysis comparing 3 different tilt degrees of the distal implants. Three-dimensional finite element models of an edentulous maxilla restored with a prosthesis supported by 4 implants were reconstructed to carry out the analysis. Three distinct configurations, corresponding to 3 tilt degrees of the distal implants (15°, 30°, and 45°) were subjected to 4 loading simulations. The von Mises stresses generated around the implants were localized and quantified for comparison. Negligible differences in von Mises stress values were found in the comparison of the 15° and 30° models. From a stress-level viewpoint, the 45° model was revealed to be the most critical for peri-implant bone. In all the loading simulations, the maximum stress values were always found at the neck of the distal implants. The stress in the distal implants increased in the apical direction as the tilt degree increased. The stress location and distribution patterns were very similar among the evaluated models. The increase in the tilt degree of the distal implants was proportional to the increase in stress concentration. The 45° model induced higher stress values at the bone-implant interface, especially in the distal aspect, than the other 2 models analyzed.

Key Words: finite-element analysis, all-on-4, full-arch prosthesis, atrophic edentulous maxilla, tilted implants, implant-bone interaction

INTRODUCTION

The severely atrophied maxilla represents a clinical challenge, and different approaches have been developed to augment available bone.1–3 Bone grafting and sinus elevation are proven treatment options; nevertheless, patients may reject these procedures because of their invasive nature, increased risk of postsurgical morbidity, and high cost.2–4 To overcome these drawbacks, some authors have suggested using tilted implants in such anatomic regions as the anterior or posterior sinus wall, the sinus septa, the palatal curvature, and the pterygoid process.5–7

The All-on-4 immediate-function approach to rehabilitate the fully edentulous jaw combines tilting and immediate-function techniques: 4 implants (2 straight medially and 2 tilted distally) are loaded with a full fixed prosthesis.6,9 The use of tilted implants (>15° with respect to the occlusal plane) in a mesiodistal direction and/or in a buccopalatal angulation enables longer implants to be inserted near the anterior wall of the maxillary sinus. The apex of these implants and the rotation fulcrum are located in the canine region, and the implant platform emerges in the second premolar or first molar region, thereby providing satisfactory molar support for a full fixed prosthesis of 10 or 12 masticatory units, respectively. Thus, placing implants parallel to anterior sinus walls with distal inclination9–11 improves bone anchorage and increases polygonal area for prosthesis support,11,12 while reducing the cantilever length and achieving a more favorable stress distribution in the bone.6,7,10,13–15

Although the use of only 4 implants for a complete fixed rehabilitation of the maxilla has been supported by clinical studies, mainly over short evaluation periods,9,16–19 some authors suggest using a larger number of implants for prosthetic treatment of an edentulous maxilla.20–23 Most studies that reported favorable results using tilted implants for the rehabilitation of the edentulous maxilla used 5 or 6 implants.11,13,22–24

The 5-year success rate ranges from 91.3% to 93.0% for tilted and 95.2% to 98.9% for axial implants.11,23 Results from radiologic analysis11 indicate that use of tilted implants has no adverse effect on bone resorption. However, questions remain relative to the amount of stress generated at the bone surrounding tilted implants.

Little experimental or long-term clinical evidence is available regarding the effect of tilting distal implants on stresses generated in prosthetic components and bone–implant interface. Finite element analyses (FEA) have shown contradictory results regarding stresses developed at the cervical bone and implant neck with tilted distal implants.25,26 Further biomechanical studies are needed to define the behavior when only 4 implants are used, with the 2 posterior implants tilted, to support a complete maxillary reconstruction. Therefore, the present study aimed to evaluate the stress patterns at the bone–implant interface of full fixed implant-supported prostheses for an edentulous maxillary arch with 4 implants as a function of the inclination of distal implants.

MATERIAL AND METHODS

The 3-dimensional (3D) geometry of the edentulous maxilla, consisting of both cortical and cancellous bone, was reconstructed from computerized tomography scans. Modeling software (SolidWorks release 2007, SolidWorks Corporation, Waltham, Mass) was used to transform the planar computerized tomography scans into a solid model of the...
maxilla. The structure symmetry permitted the reconstruction of half a maxilla. The arch had a radius of curvature of 22.5 mm and was 70 mm long, 18.9 ± 3.1 mm high, and 8.5 ± 1.25 mm wide. A 1.8 ± 0.4 mm cortical bone layer was established, overlaying the entire maxilla, whereas cancellous bone was used in the entire internal structure, simulating type 3 bone. The final model represented a rehabilitated edentulous maxilla with a completely fixed prosthesis supported by 4 implants (4.30 mm in diameter and 13 mm in length) according to the All-on-4 technique. The 2 mesial implants were modeled and positioned bilaterally and vertically in the lateral incisor regions. The 2 distal implants were placed in the second premolar regions, tilted distally. To carry out a comparative analysis, the apex of the distal implants was brought mesially to incline the implant to 15°. The tilted implant platforms were always in the same position between the second premolar and the first molar.

The 3D geometry was exported to FEA preprocessing software (ANSYS Inc, Canonsburg, Pa) and discretized in linear tetrahedral elements. A mesh of 48 700 elements and 87 200 nodes was generated for the models (Table 1). All materials were assumed to be linearly elastic, homogenous, and isotropic. Table 2 shows the Young moduli and Poisson ratios of the materials used in the present study. Boundary conditions for the model were defined according to the union of the maxilla to the base of the skull, by which the movement of the maxilla was restrained. Boundary constraints were applied to the top of the bone. The movements of the nodes in this area were completely constrained.

In order to simulate a fully osseointegrated condition, the bone–implant interface was considered completely fixed, and there were no craterlike defects around the implant neck, as well as no gaps in the implant-abutment and abutment-cylinder connections. A perfect-fit situation was assumed among the implants, the bone, and the prosthetic structure.

To evaluate and compare the distribution of stresses on the bone–implant interface, 4 loading conditions were simulated in each of the 3 model, using load values similar to those of functional bite movements from patients with All-on-4 rehabilitation (Figure 2):

- Full-mouth biting (loading 1): bilateral and simultaneous vertical static loads of 150 N were applied on the occlusal surfaces between the second premolars and the first molars, 150 N on the occlusal surfaces of the first premolars, and 100 N on the palatal surfaces on the canine;
- Anterior load (loading 2): a unilateral horizontal static load of 90 N was applied on the palatal region of the central incisors;
- Lateral load (loading 3): a unilateral horizontal static load of 90 N was applied on the palatal region of the left canine;
- Posterior load (loading 4): bilateral and simultaneous vertical static loads of 200 N were applied on the first molars (cantilever).

The results of the mathematical solutions were converted into visual results characterized by degrees of color, ranging between red and blue, with red representing the highest stress values. The color gradient table was standardized; consequently, the colors found in all the compared models represented the same quantities of stress. The results of the simulations were evaluated in terms of von Mises equivalent stress levels at the bone–implant interface.

### RESULTS

The locations and amounts of peak stress within all 4 loading situations in the 3 models are described in Table 3. Occlusal views of the maxillary bone model were captured showing the stress distribution in the peri-implant region in the cortical bone. Further views were used to show the stress distribution along the bone–implant interface in the axial and tilted implants.

In each test, the highest von Mises stress value in the peri-implant bone was used for comparison. In all the loading conditions for the 3 configurations analyzed the highest stress values were located distally at the bone–implant interface of the tilted implants. Moreover, the stress in the distal implants increased in the apical direction as the tilt degree increased.

In loading 1, full-mouth biting, the stress was concentrated in a similar manner in all the 3 models (Figure 3). The greatest stress values were found near the cortical bone around the neck of the tilted implants in the distopalatal

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Number of nodes and elements adopted for the models.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Nodes</td>
</tr>
<tr>
<td>Implant</td>
<td>8000</td>
</tr>
<tr>
<td>Bar</td>
<td>700</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>27 000</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>51 500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Young moduli and Poisson ratios of the materials used in the present study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Young Modulus (GPa)</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>13.7</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>1.37</td>
</tr>
<tr>
<td>Titanium</td>
<td>115</td>
</tr>
<tr>
<td>Type 3 gold</td>
<td>100</td>
</tr>
</tbody>
</table>
region. For the mesial implants, the stress was lower and was located in the distal region. Reduced stress was observed in the 15° and 30° models, in which there was a visible decrease in the tilted implant compared with the same implant in the 45° model.

In loading 2, an anterior guide was simulated. Stresses tended to be concentrated along the distal aspect of the tilted implants and on the buccal region of the mesial implants (Figure 4). The stress values at the bone–implant interface gradually increased as the degree of tilt increased in the
posterior regions, whereas the degree of tilt remained constant in the anterior regions.

Loading 3 simulated a canine discclusion. Although the horizontal load was applied to the area corresponding to a mesial implant, the greatest stress concentration was located on the distobuccal aspect of the tilted implant from the same side of the load (Figure 5). The stress induced on the other implants was small and appeared mainly in the same direction of the applied force. In this situation, stress around the tilted implant increased as the tilt of the implant increased, but they remained almost constant in the anterior bony region.

In loading 4, a vertical load was applied to the right and left cantilevers in the region of the first molars at the emergence of the distal tilted implants. The maximum stress values were found on the posterior region of the tilted implants (Figure 6). The stress on the implants in the 45° model was nearly double that of the other 2 models. Stresses gradually decreased moving away from the load.

**Discussion**

The aim of the present study was to evaluate stress patterns induced at the bone–implant interface in 3 different configurations of All-on-4 prosthetic rehabilitation. The FEA has been shown to be a useful tool when investigating complex systems that are difficult to standardize during in vitro and in vivo investigations. The validity of the findings depends on the precision with which the geometry, material properties, interface condition, support, and loading are in accord with physical reality. Thus, the real model and the interactions between its different parts were first studied, and then the analysis of the discretization of the numeric model with real geometries and loading type of its typical working mode was carried out.

The numeric results reported in the present study must be taken as predictions within the limitations of the models presented, because FE models represent a simplification of the actual structure. A limitation of the FE models in the present study pertains to the mechanical behavior of bone that was assumed to be linearly elastic, homogenous and isotropic. Bone is a complex living structure without a defined pattern; its characteristics vary among individuals, and its actual mechanical properties are not precisely established. The All-on-4 concept involves immediate loading and function. The FEA model used in this study assumed complete rigidity equating to full osseointegration before loading. Moreover, ideal conditions were established, such as 100% contact between bone and implant and perfect fit of implants, abutments, and prosthetic bars (absence of gaps or frictional coefficient). The perfect passivity between the components was assumed to avoid the appearance of internal tensions that could confound the analysis. Such tensions can substantially increase the risk of failure even without external loads. A perfect fit between the components combined with the framework rigidity is therefore essential to the longevity of the prosthesis.2,11

For the reasons mentioned earlier, the results of this and other FEA studies have to be seen with a critical eye. The values should not be taken as absolute but should rather be used as a comparison of the possible magnitudes of stress bone and implant components undergo during function.32–34

Masticatory forces were based on averages found in the literature for patients with implant-supported prostheses.29 However, because the models were considered to be linearly elastic, the magnitude of the load used was not as important. Furthermore, the maximum stress values were obtained for the purpose of comparing the 3 models and not for the purpose of reporting absolute values.29

Even though the maximum von Mises stress values identified in the present study were below the fatigue or the ultimate strength levels for titanium, these absolute stress values should not be directly transferred into clinical practice without proper analysis, as simplifications of the models may generate values that do not correspond to a true clinical situation. Although some authors26,35 have reported that the stress values found in their work are lower than the fracture limit of materials, such as bone and titanium, these statements may not be applied to all clinical situations.

The predictions of these numeric models confirmed previously published data and were in agreement with experimental and theoretical results obtained from the literature.29,15 The stress was located and concentrated in a similar manner in the 3 models under different load conditions. In particular, bone–implant interface was the most stressed region, and the highest tensions were located in the cortical layer around the tilted implants on the side of load application. This may be because the higher loads were applied close to these implants.25,26,35–37

In loading 1, full-mouth biting, the axial load generated only a slight increase in the maximum stress value from the 15° to the 30° configuration, whereas it increased more than 30%
by tilting the distal implants at 45°. Around the mesial implants, cancellous bone always presented a similar stress, though the cortical bone was subjected to more stress on the buccal aspect and on the occlusal surface in the mesiodistal direction in the 45° configuration. To obtain low stress values at the bone–implant interface, according to prosthetic needs, it could be advisable to achieve an axial load direction for a better stress distribution.

In loading 2, anterior guidance, the 15° and 30° configurations showed a marked difference in the stress values generated in the cancellous bone around the mesial implants, though lower stress peaks were found in the 30° model. The 45° configuration produced more stress in the buccal cortical bone. Although the load was applied close to the mesial implants, maximum stresses were always located around the distal implants. In this situation the prosthetic bar could have produced a bending moment due to the median load distributed symmetrically on the 2 distal implants. In the mesial implants the stress increased proportionally to the degree of tilt of the distal implants, and there was greater involvement of the distopalatal region in both cancellous and cortical bone.

In loading 3, which simulated the canine disclusion, a 90 N load was applied unilaterally. When the load was applied unilaterally, the implants on the opposite side were subjected to less stress, which was also observed by other authors. However, high stress levels were generated even around the tilted implant (distopalatal region) on the opposite side of the load application. This may be due to the torsion bending moment that the prosthetic bar has generated on the working side implants.

In all 3 configurations, loading 1 and 2 were evenly distributed by the system. The stress pattern increased only 20% from the 15° to the 30° configuration, whereas in the 45° configuration it increased more than 100%. In clinical cases in which the patient presents with parafunctional disease, larger surfaces for the anterior and lateral guide could be necessary for better stress distribution at the bone–implant interface.

Loading scenario 4, posterior load, was conducted to evaluate the effect of a distal cantilever. The stress pattern in
the mesial implants had the same growing involvement of the distal cortical bone in relation to the tilt degree. In the tilted implants, the maximum stress values were always located distally, and distribution showed an increase in cortical bone of the mesiopalatal region with increasing degree of tilt. The maximum stress value increased up to 200% passing from the 15° configuration to the 45° configuration. Increased stress is strongly influenced by the inclination of the implants because it increases the shear component in the system. The 45° configuration was the only one in which the cantilever load produced more stress than the axial one, as shown in Table 3. Similar results have been found by other authors, who observed a pronounced increase in stress with the presence of bilaterally cantilevered framework extensions, which, under load, created torque and moment on the implants.35,29,36,37 Previous studies have demonstrated that the increase in cantilever length is directly proportional to the increase in stress concentration in the prosthesis, implant, and surrounding bone.15,38 For a solitary implant, stress values at the bone–implant interface have been reported to increase with increasing implant inclination.39 Comparable relationships between stress values and implant inclination were obtained by other authors.35,40 However, if an implant is part of a multiple implant–supported prosthesis, the spread of the implants and stiffness of the prosthesis will reduce bending of the implant.41 Implant tilting can allow for an increase in the interimplant distance and a reduction in cantilever length so that a better load distribution can be achieved.25,36

Most clinical studies that evaluated the placement of tilted implants used 5 or 6 implants and showed favorable results.11,13,22–24 However, the use of 4 implants has shown positive results in the short term.5,16–19 A long-term study also found no significant differences in implant survival in a comparison of complete maxillary prostheses supported by 4 or 6 vertical implants.42 Although the mechanical behavior was similar in the 3 All-on-4 models, it should be emphasized that when planning a fixed rehabilitation in an edentulous maxilla using 4 implants, the quality of bone, length of the implants, patient’s habits, and length of the expected cantilever should be considered.9,15–17,29 Moreover, because reduced stress was observed in the present study in the 15° and 30° models compared with the 45° model, it may be
suggested that in clinical cases in which the patient presents with biomechanical risk factors, such as bruxism or poor bone quality, a lower tilting degree of implants, a short cantilever, or a larger number of implants may be necessary for adequate stress distribution at the bone–implant interface.

As a consequence, within the limitations of FEA modeling, possible biomechanical and clinical advantages (favorable stress distribution, anatomic structure bypass, and increase in biting elements) may have been gained by using tilted implants in the rehabilitation of the completely edentulous maxilla.

**CONCLUSION**

Within the limitations of this 3D FEA study, it could be suggested that stress location and distribution patterns were very similar between the evaluated models, which represented a complete maxillary arch restoration with 12 teeth on 4 implants. Tilting and loading distal implants increased peri-implant bone stresses compared with the stresses observed around mesial implants. Indeed, there would be negligible difference in terms of maximum von Mises stresses between the 15° model and the 30° model. The 45° model was found to induce higher stress values at the bone–implant interface, especially in the distal aspect, than the other 2 models analyzed. However, because the stress values found in this work are lower than the fracture limit of materials and because tilting implants allows us to avoid the maxillary sinus and to reduce the cantilever length, all 3 configurations of All-on-4 have been shown to be a viable and conservative solution for treating atrophic edentulous maxilla. Further in vitro tests and long-term clinical studies must be performed to validate obtained results.

**ABBREVIATIONS**

3D: 3 dimensional
FEA: finite element analysis
REFERENCES


17. Maló P, Nobre M de A, Lopes A. The use of computer-guided
flapless implant surgery and four implants placed in immediate function to support a fixed denture: preliminary results after a mean follow-up period of thirteen months. J Prosthet Dent. 2007;97:27–34.


