Optimization of Tilted Implant Geometry for Stress Reduction in All-on-4 Treatment Concept: Finite Element Analysis Study

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Purpose: The aim of this work was a finite element analysis of the effect of a sloped platform in tilted implants in the All-on-4 treatment concept on the level of maximum stresses in compact bone. Materials and Methods: Finite element modeling of the stresses at tilted microthread implants with standard and sloped abutment platform under four loading conditions and two levels of osseointegration was performed. Results: The sloped abutment platform in tilted implants positioned at rim bone level resulted in a two to four times reduction of the maximum von Mises stresses in the adjacent cortical bone compared with the standard platform. These stresses were well below the yield stress of the cortical bone. The main importance of the proposed sloped platform in tilted implants is substantial stress reduction in the case of immediate loading. The stress reduction also results in the reduction of the deformation of the framework of the All-on-4 concept. Conclusion: The suggested modification of the slope of the abutment platform on tilted implants is recommended as a technically simple and highly effective solution for significant reduction of maximum stresses in the cortical bone around the implant. Int J Oral Maxillofac Implants 2018;33:1287–1295. doi: 10.11607/jomi.6371

Keywords: All-on-4 concept, FEA, sloped abutment configuration, tilted implant

The proper fixation and position of implants with a consecutive prosthetic finalization in the mandible is due to the anatomy often limited by the location of nervus alveolaris inferior, which reduces the possibility of implant rehabilitation in the interforaminal area. The following methods are used to solve the issue: (1) short implants; (2) extension of bone volume in distal parts by vertical and/or horizontal augmentation; (3) and application of more (five or six) implants in the interforaminal area with distalization of the prosthetic base with the help of cantilever parts.

The last case with consecutive development showed that the number of dental implants may be reduced to three or four implants (Brånemark Novum), and it is finalized with an immediate or standard prosthetic loading. Another possibility is the application of tilted implants. This concept was first introduced by Krekmanov et al and later extended by Maló et al in 2003. The angle of the distal implant was increased up to 30 to 45 degrees, and implants were prolonged up to 18 mm. It enabled use of a full-arch framework for immediate loading on two frontal vertical implants (VI) and two distal tilted implants (TI) and was named the All-on-4 treatment concept (Nobel Biocare). In comparison to the methods of short implants and vertical augmentation of the ridge, the concept clinically exhibited a significant reduction in the number of complications during and after the healing period. The All-on-4 concept also has other advantages: it is relatively simple and quick, and it has a more comfortable after-surgery phase and lower rate of complications as well as lower costs. Other benefits include significant reduction of neurologic complications in terms of lesions, and the problematic locations in the mandible and maxilla can be avoided. Advantages of this concept are related to the fact that the trapezoidal part of the prosthetic support enables transfer of loading into the distal molar area during mastication. This causes the reduction of stresses in the implants and in the surrounding bone. It results in smaller stress differences between tilted and vertical implants, and subsequently also less bone loss in marginal compacts.
The research on tilted implants is focused on the optimization of placement and slope of implants to obtain more uniform load distributions and stress minimization on the implants and in the adjacent bone. The optimization of load distribution in the All-on-4 concept is usually performed using finite element analysis (FEA). FEA takes into account characteristics of the bone, morphologic specifications of implants, direction, and location of loading as well as the level of implant osseointegration.20,22–24 FEA of the immediately loaded tilted implants showed the generation of significantly higher stresses than in the case of the osseointegrated implants under the same load25,26 due to the immature bone callus with lower mechanical properties.27

The advantages of tilted implants in the All-on-4 concept were evaluated in many FEA studies.27–31 They revealed that the maximum stresses are concentrated in the upper part of the crestal bone around the implant.32–34 The increase of the implant tilt enhanced stress concentration and related problems.35,36 Maximum stresses depend on various factors. The bone density and implant bonding to the cortical bone were found to be more important than the length of the implant.37,38 Furthermore, the diameter of the implant is more important than its length.39 Geometry of the implant also plays a significant role. It was found that lower stresses were generated and stress distributions in cortical and spongious bone were more uniform in the case of implants with a conical shape compared with cylindrical implants.40–43 The use of different threads in the cortical and spongious bones on the same implant is another way to reduce the maximum stresses.44,45 Cicciù et al.46 evaluated the influence of the shape of tilted implants in the cervical area on stresses in the bone with FEA and proved that the microthreads contributed to more appropriate stress distribution.

The geometry of the interface between the implant platform and abutment can also significantly influence the maximum stresses. Schiegnitz et al. confirmed the benefits of the sloped cervical platform leveled to the surface of corticalis in vertical implants applied to the irregular alveolar crestal bone profile.47 However, the works published up to now and dealing with the optimization of implant shapes in the cervical area did not consider the position of the cervix of tilted implants in corticalis. Due to the tilt of the implant, a part of its cervix has to be above the level of the crestal bone. Thus, this part cannot contribute to the distribution of stresses in the bone. Subsequently, the optimization of cervical geometry and implant platform can provide additional possibilities for stress concentration reduction in the cervical bone in implants with different levels of osseointegration.

The aim of this work was FEA of the effect of geometry of the abutment platform in tilted implants in the All-on-4 concept on the level of maximum stresses in the adjacent compact bone. The stresses were investigated under four types of loading for immediately loaded and healed implants.

**MATERIALS AND METHODS**

**Finite Element Analysis**

Finite element analysis using ANSYS was applied to the system of the All-on-4 concept with two vertical and two tilted implants in the model bone of the mandible (Fig 1). The mandible was modeled based on the studies30,48,49 as a two-layer isotropic material with the density in the range D1–D2, which corresponds to significantly atrophied bone. The width of the modeled mandible in the basal part was 12 mm and 8 mm in the crestal area; its height was 17 mm. The thickness of corticalis was 2 mm. The interforaminal diameter of the mandible was 49 mm. Two Ti-6Al-4V Grade 5 implants (type Martikán MV 4.5-12, fa. Martikán SK) with microthreads in the cervical area were symmetrically localized in the vertical position. The distance among them was 12 mm. Two identical 45-degree tilted implants were in the distal area. Their apexes were at the distance of 5 mm from the foramen mentale. The vertical implants had a standard abutment platform leveled at the crestal surface. In the case of tilted implants, two platform geometries were investigated (Fig 1):

- with a standard abutment platform identical to the vertical implant and its upper rim leveled at the corticalis (case A in Fig 1). The abutment with a polished surface was connected to the platform, and its sloped part was in free contact with the cortical bone.
with a 45-degree sloped (marginal configuration) abutment platform (case B in Fig 1), with the marginal rim leveled at the corticalis. The abutment was completely above the bone level. The implants were connected with the framework from the same Ti alloy via abutments. The thickness of the framework was 4 mm, width 6 mm, and the median of the arch was 88 mm. The length of the distal cantilevers was 12 mm. Three-dimensional models of implants and the mandible for FEA were generated in the Pro ENGINEER program and processed in the Solid Work 2013 program. The properties of implant material, abutments, and framework corresponding to the properties of Ti alloy and those of the bone used in FEA are summarized in Table 1. The mechanical properties of the bone, implants, and framework were assumed to be isotropic. The size of finite elements in the network was optimized in dependence on the distance from the implants, maximum stresses obtained in the calculation, and minimum computing time. The size of the elements in the regions of interest was reduced until the stresses generated in the same region became constant. The final network consisted of 356,734 tetrahedral elements and 483,353 joints. The interface between the implant and bone was modeled for two extreme cases: perfectly bonded connection that simulated a fully osseointegrated implant and unbonded connection representing the immediately loaded implant without any osseointegration. The force was always applied to the centerline at the upper surface of the framework and 11 mm above the surface of the bone. Four alternatives of the vertical loading of the framework were investigated (Fig 1):

- Symmetrically on both frontal vertical implants with the force of 100 N (marked as 2xΩ-100)
- On distal tilted implants unilaterally with the force of 250 N (1xTI-250)
- On distal tilted implants bilaterally with the force of 250 N (2xTI-250)
- Bilaterally on distal parts of the cantilevers with the force of 250 N (2xΩ-250).

Lateral loading is known to produce bending moments that can increase the stress gradients in the bone around the implant.49 The intentional lateral forces were not investigated in the current work because they are indirectly present as the components of von Mises stress even during unilateral loading.50

### RESULTS

#### FEA Stresses in the Cortical Bone

Figure 2 represents the distribution of von Mises stresses in the cortical bone in all four types of loading in osseointegrated implants with a standard abutment platform. Loading of both frontal VI with the force of 100 N (load 2xVI-100) generated symmetrical distribution of stresses, and their maxima were located at the upper rims of the crestal bone adjacent to the VI (Fig 2a). The level of maximum stresses was approximately 16 MPa. In the tilted implant area, the level of stresses was only approximately 10 MPa. In the case of unilateral loading of the tilted implant (1xTI-250), the distribution was asymmetric, maximum stresses were up to 39.3 MPa, and they were also concentrated in the crestal part (Fig 2b). This stress level was 2.4 × higher than in the previous case. The stresses at all other implants were asymmetrical and reduced to approximately 10% of the stress maximum on tilted implants. Symmetrical bilateral loading of distal implants (2xTI-250) resulted in a symmetrical increase of stresses in the crestal rims up to 47.9 MPa (Fig 2a), which was approximately 22% higher than in the case of unilateral loading. Cervical parts of vertical implants were under stress of only around 4 to 6 MPa.

In the case of symmetrical loading of the framework cantilevers (2xΩ-250), the stress distribution was also symmetrical. Nevertheless, the maximum stress in the distal rims of both tilted implants reached 128 MPa. This is almost three times higher than in the previous (2xTI-250) case.

In order to determine the influence of osseointegration, analogous FEA calculations were carried out assuming no bonding between the bone and implant. In the first three types of loading, the maxima of von Mises stresses around tilted implants shifted from the upper rim to the lower inner rim of the corticalis (Figs 3a to 3c). Double maxima on the upper and lower rims were generated only in the case of 2xΩ-250 loading (Fig 3d). Absolute values of maximum stress are summarized in Table 2. It can be seen that the absence of osseointegration between the implant and the bone

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Table 1  Elastic Properties of Implant Material and Bone Used for FEA

<table>
<thead>
<tr>
<th></th>
<th>Cortical bone</th>
<th>Spongious bone</th>
<th>Implant (Ti-6Al-4V Gr.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modul of elasticity E (MPa)</td>
<td>$13.7 \times 10^3$</td>
<td>$2.3 \times 10^3$</td>
<td>$1.14 \times 10^5$</td>
</tr>
<tr>
<td>Poisson’s coefficient $\mu$ (–)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Table 2  Summary Comparison of Maximum von Mises Stresses in Cortical Bone Obtained in All-on-4 Concept on Osseointegrated and Immediately Loaded Implants with Standard and Modified Abutment Platform Geometry on Tilted Implants for Four Types of Loading

<table>
<thead>
<tr>
<th>Loading configuration</th>
<th>Maximum von Mises stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Osseointegrated</td>
</tr>
<tr>
<td></td>
<td>Standard platform</td>
</tr>
<tr>
<td>F = 100 N – two front implants (2xVI-100)</td>
<td>16</td>
</tr>
<tr>
<td>F = 250 N – one tilted implant (1xTI-250)</td>
<td>39</td>
</tr>
<tr>
<td>F = 250 N – two tilted implants (2xTI-250)</td>
<td>48</td>
</tr>
<tr>
<td>F = 250 N – both ends of the cantilevers (2xΩ-250)</td>
<td>128</td>
</tr>
</tbody>
</table>
resulted in 2.3 to 3.3 times increase of the maximum stresses in all types of loading.

Similar simulations were carried out for the implants with a 45-degree sloped abutment platform (case B in Fig 1). In the case of osseointegrated implants, the maximum stresses were always on the upper rim of the corticalis (Fig 4), similar to the implants with standard geometry (Fig 3). Differences resulted from the presence of microthreads that were in contact with the corticalis. In the case of symmetrical loading of VI (2xVI-100), maximum stress up to 21 MPa was reached compared with 16 MPa for the standard platform (Table 2). However, in all other types of loading, the values of maximum stresses were between 42% and 61% of the values obtained for standard platform implants.

The absence of osseointegration in the case of implants with a modified abutment platform had similar qualitative effects as in the case of standard geometry of the implant. Stresses were also concentrated at the rim of the corticalis, and they were strongly influenced by the presence of microthreads (Fig 4). However, the absolute values were higher by 14% to 81% depending on the way of loading (Table 2).

**FEA of the Deformation in the Framework**

Figures 2 to 5 illustrated the stress distributions with the focus on the areas with the maximum von Mises stresses between the implant and adjacent corticalis. Although the stress is directly related to strain via Young’s modulus, the effects of loading on the whole studied system can be visualized in terms of displacements. Figure 6 and Table 3 summarize distributions of deformation of the framework and mandible and their maximum values for various cases of loading, respectively. It can be seen that 2xVI-100 loading resulted in symmetrical displacements of the front part of the mandible and framework down while the distal parts shifted upward. The maximum displacements were...
obtained in the case of cantilever loading (2xΩ-250).
All the other types of loading generated significantly
smaller deformations. However, the data in Table 3 rep-
resent only the maximum values from the locations of
their concentration. General strain distribution can be
visualized from the displacements along the centerline
on the upper surface of the framework. Figure 6 shows
it for both geometries and osseointegration levels. The
comparison of these curves in Fig 6a for 2xVI-100 load-
ing indicates that the proposed modification of the
implant geometry decreased the displacements along
the whole framework and reduced the differences
between osseointegrated and immediately loaded
implants. Figures 6b to 6d represent displacement

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**Fig 6** Side and frontal views of the displacements in the studied All-on-4 concept and their distributions
along the centerline on the upper surface of the framework for osseointegrated and immediately loaded
implants with standard and sloped abutment platform under various loading configurations: (a) 2xVI-100N,
(b) 1xTI-250 N, (c) 2xTI-250 N, and (d) 2xΩ-250 N. The displacements are intentionally 10× magnified for
better visibility.
into the irregular alveolar ridge, the present work suggests that even though the first applications of implants with a sloped platform were indicated for vertical orientation integration. It is in perfect agreement with the previously obtained results on stress reduction.

**DISCUSSION**

Despite the aforementioned variability of the absolute values is determined by the assumptions involved in the models used for the calculations. The obtained stress values are valid for the properties of the cortical and spongious bone indicated in Table 1, which correspond to the average values for bone density D1–D2 taken from the literature. The assumed geometry of the mandible also applies to the common anatomical proportions. The level of osseointegration was limited to two cases of zero and full bonding. The critical parameters related to torque and stability during implant introduction for immediate loading were not considered. All these factors can differ for the individual situations that would affect the absolute values of the maximum von Mises stresses. Thus, the attention should be focused on the relative changes of the maximum stresses due to the proposed implant platform geometry modification.

Despite the aforementioned variability of the absolute values of von Mises stresses, the obtained maxima need to be compared with the bone properties to estimate survivability of the implant. The concept of von

### Table 3 Summary of Maximum Vertical Displacements of Studied All-on-4 Framework with Osseointegrated and Immediately Loaded Implants, with Standard and Sloped Abutment Platform Geometry on Tilted Implants for Four Types of Loading

<table>
<thead>
<tr>
<th>Loading configuration</th>
<th>Osseointegrated bonded implant (µm)</th>
<th>Immediately loaded unbonded implant (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard platform</td>
<td>Sloped platform</td>
</tr>
<tr>
<td>F = 100 N – two front implants (2xVI-100)</td>
<td>+6.1/–27</td>
<td>+8.8/–31</td>
</tr>
<tr>
<td>F = 250 N – one tilted implant (1xTI-250)</td>
<td>+2.9/–16</td>
<td>+3.7/–26</td>
</tr>
<tr>
<td>F = 250 N – two tilted implants (2xTI-250)</td>
<td>-13/–21</td>
<td>-23/–25</td>
</tr>
<tr>
<td>F = 250 N – both edges of the cantilevers (2xΩ-250)</td>
<td>+26/–150</td>
<td>+31/–200</td>
</tr>
</tbody>
</table>

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Mises stresses was originally developed to evaluate the onset of plasticity in ductile metals under complex loading by means of the comparison with the yield strength obtained from the uniaxial tests. The applicability of this approach to bone might have limitations. However, it still may be useful to compare the obtained maxima of von Mises stresses with the bone yield strength of the corticalis. The yield stress values in human and bovine bones in the longitudinal direction of approximately 111 ± 19 MPa and 117 ± 4 MPa, respectively, were reported. The comparison with the values in Table 2 indicates that in the standard platform, the yield stress was exceeded in three of four loading cases after immediate loading. In the loading cases with the sloped platform, the stresses were significantly lower than 120 MPa in all but one case (frame ends and immediate loading). Obviously, a sloped platform provides reasonable safety margins even in the cases of loads considerably exceeding common masticatory forces. A direct benefit of the sloped platform includes smaller and more proportionally distributed stresses, which reduce risk of bone resorption around the implant. Subsequently, a higher implant survival rate can be expected after immediate loading and also in the osseointegrated implants. Moreover, a sloped tilted implant platform loaded after immediate application would exhibit a protective effect not only on the bone but also on the soft tissues.

Despite some limitations of the absolute values of the calculated maximum stresses, it was clearly demonstrated that the suggested modification of the slope of the abutment platform on tilted implants results in significant maximum stress reduction. Thus, it is highly recommended as a technically simple and very effective solution for significant stress concentration suppression and strain reduction in the cortical bone for immediately loaded and osseointegrated implants. From a technical viewpoint, implants with a sloped platform for different indications are already available in the market. Such modification of their use can be easily applied to any type of existing implant.

CONCLUSIONS

FEA of the stress distributions in and around tilted implants in the All-on-4 concept revealed the following. The sloped abutment platform in tilted implants positioned at the rim bone level resulted in a two to four times reduction of the maximum von Mises stresses in the adjacent cortical bone compared with the standard platform. These stresses were well below the yield stress of the cortical bone. The main importance of the proposed sloped platform in tilted implants is substantial stress reduction in the case of immediate loading. The stress reduction also results in the reduction of the deformation of the framework of the All-on-4 concept. The stress reduction due to the sloped platform in tilted implants is expected to suppress the resorption processes in the marginal alveolar bone and in soft tissues even for immediate applications. It would also reduce the risk of the bone and framework overloading and extend the lifetime of implant prosthetic treatment.

The suggested modification of the slope of the abutment platform on tilted implants is recommended as a technically simple and highly effective solution for significant reduction of maximum stresses in the cortical bone around the implant.

ACKNOWLEDGMENTS

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REFERENCES


