Bone stress when miniplates are used for orthodontic anchorage: Finite element analysis

Yen-Wen Huang, Chih-Han Chang, Tung-Yiu Wong, and Jia-Kuang Liu

Tainan, Taiwan, ROC

Introduction: The success rate of miniplates is superior to that of other temporary anchorage devices; nevertheless, the biomechanical behavior of miniplates during orthodontic use is not totally understood. The aim of this study was to investigate bone stress by finite element analysis when miniplates are used for orthodontic anchorage.

Methods: A 3-dimensional model consisting of a bone block integrated with a miniplate and fixation screw system was constructed to simulate various types of miniplates, screw numbers, screw lengths, cortex thicknesses, and force magnitudes and directions. Results: The peak von Mises cortex stress values were highest with the I-type plates followed by the L-type, Y-type, and T-type plates. Bone stress decreased as the screw numbers increased but was not related to screw length. Bone stress increased as the cortex thickness decreased. Bone stress was linearly proportional to the force magnitude, and the highest values were produced when the force was in the forward direction. Conclusions: When a T- or Y-type plate is used, or when the force direction is in the tensile mode, bone stress decreases. Bone stress also decreases as the screw numbers increase and as the cortex thickness increases. Furthermore, it decreases as the force magnitude becomes less. (Am J Orthod Dentofacial Orthop 2012;142:466-72)

A
nchorage control is an important factor for the success of orthodontic treatment. Conventional anchorages might be neither sufficient nor efficient in some critical cases when there is poor patient compliance or dental conditions are poor. In 1983, the first clinical use of a screw for orthodontic anchorage was reported. After that, temporary skeletal anchorage devices were rapidly developed. There have been 3 major trends in the field of temporary skeletal anchorage devices: palatal implants, miniscrews, and miniplates. When compared with the other temporary skeletal anchorage systems, miniplates offer better stability. The average failure rates are 7.3% for miniplates, 10.5% for palatal implants, and 16.4% for miniscrews.

In the history of miniplate anchorage in orthodontics, the first use of a surgical bone plate for orthodontic anchorage was reported in 1985. Since that time, a number of miniplate systems have been specially designed as orthodontic anchors. A skeletal anchorage system, with its anchor plates and screws made of pure titanium, was developed in 1999 for use as absolute orthodontic anchorage units. The skeletal anchorage system was monocortically placed, and this allowed rigid anchorage because of the osseointegration effects on both the anchor plates and the screws. The failure rate of the skeletal anchorage system is 6%, and it shows excellent clinical performance. A zygomatic anchorage system, consisting of plates and screws, also a rigid anchorage system, was introduced in 2002. The success rate of the zygomatic anchorage system was 98.6%. In another example, a locking plate (Compact lock 2.0) has been used as posterior maxilla anchorage, and its success rate is 93.4%. Although the success rates of miniplates are superior to those of other temporary skeletal anchorage devices, the biomechanical behavior of miniplates during orthodontic use is still not totally understood. Therefore, the aim of this study was to investigate bone stress associated with various miniplate systems by using finite element analysis and taking into account the various types of plates available, the fixation screw numbers, the fixation screw lengths, the cortex thicknesses, the loading force magnitudes, and...
the loading force directions, with the aim of understanding the effects of these variables on orthodontic anchorage.

MATERIAL AND METHODS

A 3-dimensional model with a bone block integrated with a miniplate was constructed by using a finite element analysis program (Dassault Systèmes; SolidWorks, Concord, Mass). This simulated a miniplate screwed into bone as an orthodontic anchorage unit. The bone block, which consisted of cortical bone and cancellous bone, was simplified to be 30 mm in length, 30 mm in width, and 25 mm in height for the evaluation. The miniplate and miniscrew geometries were based on the Mondeal System (Tuttlingen, Germany). The fixation screw had a thread profile that consisted of an isosceles triangle of 0.4 mm in height and 0.16 mm at the base, with a thread pitch of 1.0 mm. The diameter of the fixation screw was 2 mm. All materials in the model were considered homogeneous, isotropic, and linearly elastic. The fixation screw and bone plate were assumed to be pure titanium with a Young’s modulus of 110 GPa and a Poisson’s ratio of 0.35. The Young’s moduli of the cortical and cancellous bone were assumed to be 14 GPa and 1.3 GPa, respectively, and the Poisson’s ratio was 0.3 for both. The interface between the cortex and the cancellous bone was assumed to be fully bonded. Contact interface conditions were modeled between the bone structure and the plate system as well as between the plate and the fixation screws. The model was meshed with 4-node tetrahedral solid elements as shown in Figure 1.

To determine the plate and fixation screw effects, 4 types of plates—L type, T type, Y type, and I type (Fig 2)—with 3 screw lengths (5, 7, and 9 mm)—as well as the use of either 2 or 3 screws were investigated. The screw length was measured to include the screw head, which had a height of 2 mm. To study the effect of cortex thicknesses, 3 values were simulated: 0.25, 0.5, and 1.0 mm.

To determine the loading effect, 3 force magnitudes (2, 4, and 6 N) and 2 force directions (in-plane force and off-plane force) were investigated. The in-plane force was defined as when the loading force vector was lying on the plate plane, the x-z plane. The z-axis was determined as the axis of the plate’s long arm, whereas the x-axis was perpendicular to the z-axis, with the plate plane pointing in the direction of the short arm of the L-type plate. The y-axis was thus determined by the cross-product of the z-x axis in right coordinate system, and the y direction correspondingly was normal to the superior surface of the bone block (Fig 3, A). For the first loading group (in-plane force; $y = 90^\circ$) (Fig 3, B), 3 loading modes were evaluated: forward bending ($x = 0^\circ$), tensile force ($x = 90^\circ$), and backward bending ($x = 180^\circ$). For the second loading group (off-plane force) (Fig 3, C), 3 loading modes were investigated involving a y force component added into the in-plane forward bending force ($x = 0^\circ$). This created force directions with respect to the y-axis of 60° (downward), 90° (no downward and no upward force), and 120° (upward).

RESULTS

The base model was designed to have a 1-mm cortical bone thickness and to use an L-type bone plate fixed with 2 miniscrews (length, 5 mm); this was subjected to 2 N of forward bending force. Figure 4 shows the distribution of the von Mises stress values in all elements of the base model. Under the force, the long arm of the bone plate was under bending mode with the largest peak of von Mises stress occurring in the bone plate. The values of the peak von Mises stress of the plate, screw 1, screw 2, cortex, and cancellous bone were estimated as 101, 43.2, 23.1, 10.2, and 5.13 MPa, respectively. The peak stress of the bone plate was concentrated under the first miniscrew. For both screws, the peak stress occurred at the screw head. In general, the stress value of the first screw was larger than that of the second screw. In terms of cortical and cancellous bone, the peak stresses were also concentrated around the screws (Fig 5). As for the displacement result, bending
deformation was identified in the long arm of the plate (a gap was observed between the screw and the bone structure), and the largest displacement occurred at the loading site (Fig 6).

As the bone plate type of the base model changed, there were also significant changes in the peak von Mises stress values of the bone structure. The peak values of the von Mises stress affecting the cortex were 12.42 MPa for an I-type plate, and lower values for the L-type, Y-type, and T-type plates in that sequence. With the stress of the base model set at 1, the stress ratios of the plate types are shown in Table I. As the plate changed from L type to T type and then to Y type (a symmetrical plate with short arms), the stress values in the cortex decreased by about 50% and 30%, respectively. As the plate changed from L type to I type (symmetrical plate without short arm), the stress in cortex increased by about 20%.

When changing the screw length of the base model, the changes in the peak von Mises stress values in the bone structure were insignificant. The smallest peak von Mises stress occurred with the 5-mm model and the base model, and these had values of 10.24 MPa in the cortex and 5.13 MPa in cancellous bone. With the stress of the base model set at 1, the stress ratios of the cortex as the screw length varied were 1.16 and 1.14 for 7-mm and 9-mm screws, respectively. Thus, as the screw size increased from 5 to 9 mm, the stress did not decrease but, rather, increased by 14%. So, the relationship between screw length and bone stress was not uniform.

The effect of screw numbers was based on the outcomes for the T-type and Y-type plates. By using the same loading and bone structure as the base mode, both plates were secured with 2 or 3 screws. With a 2-miniscrew fixation, the screws were arranged in
a symmetrical manner. Then when a third screw was added, it was always at the center (Fig 7). In general, adding an extra screw at the center reduced the bone stress by 11% to 23%. With the T-type plate, when including the third screw, the peak von Mises stress values of the cortex decreased from 4.80 to 4.25 MPa. Similarly, for the Y-type plate, the stress values decreased from 7.09 to 5.49 MPa.

When the cortical thickness of the base model was changed, the peak von Mises stress in the bone structure was moderately affected. With the stress of the base model set at 1, the stress ratios for cortex thicknesses of 0.25, 0.5, and 1 mm are shown in Table II. The lowest peak von Mises stress occurred with the 1-mm model; as the cortex thickness decreased to 0.5 mm and then 0.25 mm, the stress values increased by 20% and 46%, respectively.

When the force magnitude of the base model was changed, the peak von Mises stress in the bone structure showed a linear increase. Thus, from 2 to 4 N and then from 4 to 6 N, the stress increased by almost 100% and 200%, respectively, as shown in Table III. When the in-plane force direction was changed with respect to the base model, the changes in peak von Mises stress values in the bone were significant. With the stress of the base model set at 1, the stress ratios varied as the force direction changed, as shown in Table IV. As the force changed from forward bending (x = 0°) to along the long arm of the plate (x = 90°; tensile mode) or to backward bending (x = 180°) away from the short arm, then the stress values decreased by 69% and 14%, respectively. Furthermore, changing the off-plane force direction of the base model also resulted in obvious variations in the von Mises stresses of the cortex. As the direction was changed from y = 90° (no downward or upward bending) to y = 60° (downward bending) and then to y = 120° (upward bending), the stress values decreased.

**Fig 4.** Distribution of von Mises stresses in the base model: A, all elements; B, screw 1 (S1); C, screw 2 (S2); D, miniplate; E, cortex; and F, cancellous bone.
by almost 38% and 27%, respectively. However, when adding the downward or upward force component into the in-plane tensile force mode, there was an increase in cortex stress, and this was different from what occurred with the in-plane forward force mode, as shown in Table IV.

**DISCUSSION**

There are various types of miniplates: I type, L type, Y type, and T type; the choice of plate depends on the anchorage bone area.14 There was no significant difference between the L- and T-shaped miniplates in terms of mobility and failure rate.15 In 1 finite element simulation, the peak von Mises stress values of the cortex for the I-type plate were higher than those of the L and T types.16 We noted similar finding in this study, with the I-type plate having the highest peak stress for the

<table>
<thead>
<tr>
<th></th>
<th>L type</th>
<th>T type</th>
<th>Y type</th>
<th>I type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (MPa)</td>
<td>10.24</td>
<td>4.80</td>
<td>7.09</td>
<td>12.42</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.47</td>
<td>0.80</td>
<td>0.69</td>
<td>1.21</td>
</tr>
<tr>
<td>Stress (MPa)</td>
<td>5.13</td>
<td>4.11</td>
<td>1.36</td>
<td>4.66</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.26</td>
<td>0.92</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig 5. The distribution of von Mises stresses in the basal model (cross-sectional view): A and B, all elements at the fixation screw area; C, fixation screw area.

Fig 6. A, Displacement of the base model (300 times), a cross-sectional view; B, fixation screw area.
cortex, followed by the L type, the Y type, and the T type in that order. This can be explained by the short arms of the plates helping with stability and the increased symmetry of the plates.

The peak von Mises stress values of the cortex fixed with 3 screws were higher than the values with 2 screws with the I-type plate. In our study, the peak stress of the cortex fixed with 3 screws was lower than with 2 screws for the Y type and T type. Thus, adding 1 fixation screw to the center of a symmetrical plate seems to increase stability. The difference in results might be due to the direction of alignment of the fixation screw. The direction of alignment of fixation screws with the I-type plate is vertical, but that of the Y-type and T-type plates is horizontal.

Previous finite element studies found that cortex thickness determines the overall load transfer from the miniscrew to bone, and the density of cancellous bone plays only a minor role in resisting this force. These authors suggested that a cortical bone thickness of 1 mm improved the success rate of miniscrews. In our study, the von Mises stress trend for variations in cortex thickness was similar to previous studies, and a cortical thickness of 1 mm had the lowest von Mises stress, with increases of 20% and 46% for 0.5 and 0.25 mm of cortical thickness. Therefore, increased cortex thickness can increase the stability of the miniplates.

In animal studies, it was shown that the magnitude of the force does not influence failure after loading; however, the forces used were less than 150 g. In a clinical study, 150 or 450 g of force did not affect the success rates of a zygomatic plate-screw anchorage system. In this study, force magnitude and the peak von Mises stress in the cortex were linearly related, and 6 N created 3 times the stress on the bone compared with the base model. Of all investigated factors, the force

---

**Table II.** Peak stress values of bone with different cortical thicknesses

<table>
<thead>
<tr>
<th></th>
<th>1 mm</th>
<th>0.5 mm</th>
<th>0.25 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio</td>
<td>1</td>
<td>1.20</td>
<td>1.46</td>
</tr>
<tr>
<td>Cortex</td>
<td>10.24</td>
<td>12.37</td>
<td>15.01</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>5.13</td>
<td>6.71</td>
<td>6.12</td>
</tr>
</tbody>
</table>

**Table III.** Peak stress values of cortex with different force magnitudes

<table>
<thead>
<tr>
<th></th>
<th>2 N</th>
<th>4 N</th>
<th>6 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio</td>
<td>1</td>
<td>1.30</td>
<td>1.19</td>
</tr>
<tr>
<td>Cortex</td>
<td>10.24</td>
<td>20.48</td>
<td>30.72</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>5.13</td>
<td>10.26</td>
<td>15.39</td>
</tr>
</tbody>
</table>

---

**Table IV.** Peak stress values of cortex with different force directions

<table>
<thead>
<tr>
<th></th>
<th>y = 90°</th>
<th>y = 60°</th>
<th>y = 120°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio</td>
<td>1</td>
<td>1.20</td>
<td>1.46</td>
</tr>
<tr>
<td>x = 0°</td>
<td>10.24</td>
<td>6.38</td>
<td>7.45</td>
</tr>
<tr>
<td>x = 90°</td>
<td>3.21</td>
<td>6.71</td>
<td>7.39</td>
</tr>
<tr>
<td>x = 180°</td>
<td>8.85</td>
<td>10.20</td>
<td>6.17</td>
</tr>
</tbody>
</table>

---

Fig 7. A, Two screws with the T-type miniplate; B, 3 screws with the T-type miniplate.
magnitude seems to play the most important role in the bone-stress responses with respect to the plate-screw system. Therefore, a high loading force should be avoided. The peak von Mises stress values on the cortex of the miniplates were smallest for direction x = 90° when using the in-plane force system. This tensile force is similar to the vertical force used for intruding teeth in clinical situations. A horizontal force induces higher stress than does a vertical force. This point supports the results of some previous finite element studies that suggested avoiding or minimizing horizontal forces on implants to reduce stress.\textsuperscript{19,22,23} It was noted that backward direction force (force direction opposite the direction of the short arm) reduced the stress by 14% when compared with forward force (force direction the same direction as the short arm) in the L-type plate. With the off-plane force, the force direction is changed to downward or upward, similar to an inward or outward direction in clinical use, and this could reduce the force by 38% or 27%, respectively.

**CONCLUSIONS**

Based on the finite element analysis simulations from this study, we concluded the following.

1. Bone stress is decreased when symmetrical plates with a short arm are used, such as the T-type and Y-type miniplates.
2. Bone stress is decreased when the number of fixation screws is increased and with greater cortex thickness.
3. The peak von Mises stress on the cortex increased linearly with increasing force.
4. Tensile force resulted in lower bone stress than forward force with the in-plane force system; furthermore, downward or upward force can reduce stress for the off-plane force system.
5. Fixation screw length seemed to have no significant effect on bone stress.

**REFERENCES**