Original article

Strain of bone-implant interface and insertion torque regarding different miniscrew thread designs using an artificial bone model

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Summary

Objectives: To evaluate the initial stability of dual-thread miniscrews by analyzing the strain at the bone-implant interface and insertion torque during implantation in artificial bone models with different cortical bone thicknesses.

Materials and methods: Insertion torque, and strain, measured with a five-element strain gauge in 1.0, 1.5, and 2.0-mm artificial cortical bone, during insertion of single- (OAS-T1507) and dual-thread (MPPlant-U3) type self-drilling miniscrews were assessed.

Results: Both dual- and single-thread miniscrews showed greater than 7790 μstrain for all cortical bone thicknesses, and dual-thread miniscrews reached up to 19580 μstrain in 2.00 mm cortical bone. The strain of dual-thread miniscrews increased with increasing cortical bone thicknesses of 1.0–2.0 mm. For single-thread miniscrews, the maximum insertion torque was relatively constant, but maximum insertion torque increased significantly in dual-thread groups with increasing cortical bone thicknesses (P < 0.0001). The maximum insertion torque with all cortical bone thicknesses was significantly lower with single- than dual-thread types (P < 0.0001).

Conclusions: Self-drilling dual-thread miniscrews provide better initial mechanical stability, but may cause strain over the physiological bone remodelling limit at the bone-implant interface in thick cortical bone layers.

Introduction

In orthodontic treatments, anchorage preparation is an essential part of obtaining aesthetic appearance and normal occlusion. Among various skeletal anchorages, the orthodontic miniscrew is small in size, enabling it to be placed in various areas without damaging teeth or other anatomic structures. With easy insertion and removal, miniscrews are used in various clinical situations, and many successful cases have been reported (1–7). However, the clinical applications of the miniscrews do not guarantee successful treatments in all cases in which they are applied, and stability is the basic prerequisite for using the miniscrew as a skeletal anchorage.

The biological stability of miniscrews can be evaluated according to the screw design and loading time using experimental animals (8–12). To conduct mechanical stability tests based on miniscrew design, insertion and removal torque measurements (8, 13–16) and pull-out strength measurements (13, 17–19) are widely used. These
mechanical analyses show that both the screw design and bone quality and quantity in the insertion area affect the stability of miniscrews after implantation.

Measurements of the insertion torque are used to predict the initial stability of a miniscrew. However, insertion torque can be measured only during insertion of miniscrews and cannot be used to evaluate their stability for a certain period after insertion. On the other hand, a histomorphometric analysis can be applied to evaluate new bone formation at the bone-interface and the bone density surrounding the implant, which is mostly used in animal studies using tissue specimens.

As one of the mechanical methods to evaluate miniscrew stability, measurement of strain or stress at the bone-implant interface after insertion has been carried out. The strain at the cortical bone layer during the implantation of self-tapping screws was analyzed by three-dimensional finite element analysis and was much >4000 µstrain during implantation (20). Moreover, other finite element studies measured the strain on the cortical bone layer induced by self-drilling placement of orthodontic micro-implants, which showed high bone strains well >40000 µstrain in the peri-implant bone of the cortical layer (21). These strains, which are 10 times higher than the physiological limit allows, predicted a negative impact on the physiological remodelling of cortical bone near the implant after implantation.

Bone remodelling and tissue reorganization following orthodontic loading onto implants was reported in different subjects with different loading types, using both finite element analysis with micro-computed tomography scanning and histological analysis of the alveolar bone of monkeys (22). The study concluded that the strain was most concentrated in the cortical bone layer, and a high level of remodelling was found near the implants.

The dual-thread miniscrew was recently developed and is currently in use today. The dual-thread shape increases the screw’s contact area with the cortical bone, which can improve the stress distribution and initial stability (23). However, the results from the previous study were limited by the absence of a cortical bone layer in the artificial bone model, and only insertion and removal torque were measured, which are indirect measurements of the strain near the implant.

Since conventional studies on the stress distribution during implantation use strain values calculated from computer simulations, the actual strain values using mechanical strain sensors could be different from the results of finite element analysis. Even though the maximum insertion and removal torques were used to evaluate the stability of miniscrews, information related to strain generated at the miniscrew-bone interface during implantation is still insufficient. Therefore, a direct measurement of generated strain at the bone-implant interface during implantation is needed to validate the previous results from finite element analysis.

The purpose of this study was to evaluate the initial stability of the dual-thread miniscrew by analyzing the strain at the bone-implant interface and the insertion torque during the implantation of miniscrews in cortical bone of different thicknesses using artificial bone models.

Materials and methods

Ti-6Al-4V ELI orthodontic miniscrews (Biomaterials Korea Inc., Seoul, Korea) were used and the samples were divided into single-thread (OAS-T1507) and dual-thread (MPlant-U3) types (Figure 1, Table 1). All miniscrews were inserted into an artificial bone block using a torque testing machine (Biomaterials Korea Inc.) without predrilling. The torque testing machine was constructed based on ASTM 543-02 with a fixed 1.470 kg loading force.

![Figure 1. Schematic diagram of single- and dual-thread type miniscrews.](image)

| Table 1. Description of miniscrews tested in this study (unit: mm) |
|-----------------------------|-------------|-------------|
| Type                        | Measurement |             |
| T1507                       | D1          | 1.45        |
|                             | D2          | 1.50        |
|                             | d           | 0.95        |
|                             | d<sub>n</sub> | —           |
|                             | L<sub>1</sub> | 6.00        |
|                             | L<sub>2</sub> | 7.00        |
|                             | P            | 0.70        |
| U3                          | P<sub>D</sub> | 0.35        |

Solid rigid polyurethane foam (Sawbones, A Division of Pacific Research Lab Inc., San Francisco, California, USA) with a density of grade 5 (0.80 g/cc) and 1148 MPa of modulus was used as artificial cortical bone. The thicknesses of the artificial cortical bone layer were varied at 1.0, 1.5, and 2.0 mm, and each layer was attached to a solid rigid polyurethane foam block of grade 2 (0.32 g/cc) and 210 MPa of modulus using cyanoacrylate resin adhesives.

Strain measurement

Five-element strain sensors (KFR-015-120-D9-11N10C2, Kyowa, Tokyo, Japan; resistance 120.0 ± 15.0 Ω; gauge factor 2.00 ± 1.5 per cent) were attached to estimate the strain at the artificial bone surface. The gauge length, pitch, and grid width were 0.15, 0.5, and 0.34 mm, respectively.

The artificial bone surface, which had a sensor attached at the insertion point, was rubbed with cloth to create a uniform surface. After removal of remnants from the surface using rosin solvent (M-line...
Regression equation for miniscrew interface strain measurement

The regression equation was constructed by measuring strain over time during implantation using a five-element strain sensor with 0.5 mm spaces between each element, and the convergence of each equation model was calculated. The regression equation for estimating strain at the miniscrew-bone interface provides y-intercepts as estimated strain values during the entire implantation process, which is shown in a graph as a continuous function. To calibrate the strain value at the miniscrew-bone interface, the distance between the inserted miniscrew and its corresponding sensor was measured for each test using a stereomicroscope (Olympus SZ61, West Palm Beach, Florida, USA). Artificial cortical bone with different cortical layer thicknesses was used to measure the strain of single- and dual-thread miniscrews. Four miniscrews were inserted into each artificial bone specimen.

**Insertion torque measurement**

Twelve of each of the two types of miniscrews were inserted into each of three different thicknesses of artificial cortical bone, and the torque (insertion torque, Ncm) value was measured at maximum insertion. Using a torque tester (Biomaterial Korea Inc.), the insertion torque was continuously measured by applying five revolutions per minute of a fixed clockwise rotation. After placing a miniscrew vertically on the artificial bone block, the torque values were recorded every 0.1 seconds using a computer program (QuickDataAcq, Santa Clara, California, USA) during the entire implantation procedure. The insertion depth of each miniscrew was accurately controlled within 0.01 mm of depth error with a dial indicator (Caliper 500, Mitutoyo, Kawasaki, Japan). Twelve miniscrews were inserted into each bone specimen.

**Statistical analysis**

Using five-element strain gauges, which were attached near the interface of the miniscrew, the regression equation for the strain of the miniscrew interface was formulated by measuring strains with constant inter-sensor distance. Strain curves based on equations derived from different cortical bone thicknesses were established. Using a two-way analysis of variance, maximum insertion torque and total insertion time according to cortical bone thickness and miniscrew thread designs were tested to find statistical significance. Tukey test was performed as a post hoc analysis.

**Results**

**Strain measurement according to cortical bone thickness**

In the 1.0 mm thick cortical bone, the maximum estimated interface strain of a single-thread miniscrew was 13 450 μstrain, and the strain at final insertion was 7790 μstrain. The maximum interface strain was 15 860 μstrain for a dual-thread type miniscrew, and strain at final insertion was 15 300 μstrain (Figure 3).

With cortical bone thickness of 1.5 mm, a single-thread type miniscrew had a maximum interface strain of 18 410 μstrain and the strain at final insertion was 12 470 μstrain. For a dual-thread type miniscrew, the maximum interface strain was 17 760 μstrain, and the strain at final insertion was 13 560 μstrain (Figure 3).

In the 2.0 mm thick cortical bone, the maximum interface strain of a single-thread type miniscrew was 25 500 μstrain, and the strain at final insertion was 20 370 μstrain. For a dual-thread type miniscrew, the maximum interface strain was 24 800 μstrain, and the strain at final insertion was 19 580 μstrain (Figure 3).

**Maximum insertion torque measurement according to cortical bone thickness and miniscrew design**

With cortical bone thicknesses of 1.0, 1.5, and 2.0 mm, the maximum insertion torques for a single-thread type miniscrew were 9.1, 10.0, and 9.8 Ncm, respectively, and there were no significant differences between groups. However, the maximum insertion torques...
for the dual-thread type miniscrew were 10.6, 13.8, and 15.8 Ncm, respectively, which showed significant differences between the different cortical bone thicknesses ($P < 0.0001$; Table 2, Figure 4). The insertion torque of the dual-thread type miniscrew was significantly greater than that of the single-thread group for each cortical bone thickness.

**Figure 3.** The changes in strain with the single-thread and dual-thread miniscrews in different cortical bone thicknesses. Estimated strains at the miniscrew-bone interface were provided by intercepts of the regression equations, which were derived from the input data of the five-element sensors (D1, D2, D3, D4, and D5).

**Table 2.** Changes in maximum insertion torque depending on cortical bone thickness and the type of miniscrew

<table>
<thead>
<tr>
<th>Cortical bone thickness (mm)</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum insertion torque (Ncm)</td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>Single thread</td>
<td>9.1</td>
<td>0.6</td>
<td>10.0</td>
</tr>
<tr>
<td>Dual thread</td>
<td>10.6</td>
<td>0.7</td>
<td>13.8</td>
</tr>
<tr>
<td>Significance</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

NS, statistically nonsignificant, *$P < 0.0001$. 
Discussion

Artificial bone block has been used to investigate the influence of various miniscrew design factors on insertion torque and pull-out strength (24–26). Although histological analysis from animal experiments may seem like a better method for evaluating biological response, it is also difficult to control for confounding factors like variations in bone density and cortical bone thickness in the insertion area (9, 27, 28). In this study, an artificial bone model was constructed that had uniform density and thickness in order to objectively obtain empirical data. A range of maximum insertion torques were measured as is similarly done with human alveolar bone (29), showing that the artificial bone block has physical properties similar to those of human bone (30).

Bone remodelling is affected by strain surrounding the implant (31). It was proposed that regions of cortical bone subjected to strains >2000–3000 µstrain are functionally overloaded (32, 33) and will lead to new bone formation to reduce the bone strain in those regions. Strains >4000 µstrain would be pathological and lead to bone resorption that outpaces bone formation (34). Strains at the bone-interface from the present study ranged between 7790 and 20,000 µstrain, which is lower than that obtained from previous finite element analyses using a self-drilling type of miniscrew (21). However, the strain generated during implantation was much greater than the physiologically allowed value, and a closer implant interface significantly and quadratically increased the strain. Excessive strain may have a negative impact on the physiological processes that occur during cortical bone remodelling at the miniscrew interface, with marginal bone loss and necrosis at the bone-interface expected (35).

The strain at the bone-implant interface increased with increasing cortical bone thickness. It was reported that miniscrews have a higher success rate in cortical bone thicknesses of 1 mm or greater because the stress at the bone-implant is distributed into the surrounding bone (36). However, since strain at the bone-implant interface rose with increasing cortical bone thickness, stability at strain values over the biological limit needs to be evaluated in animal studies.

In this study, the strain between the single-thread and dual-thread type miniscrews was similar at a cortical bone thickness of 1.0 mm, but the discrepancy between miniscrew types widened to >10,000 µstrain with increasing cortical bone thicknesses. This result was induced by the different miniscrew thread designs. The inter-thread distance is 0.7 mm for the single-thread group, and 0.35 mm for the dual-thread group, which had a wider internal diameter along half of the whole thread compared with the single-thread type.

A single-thread type showed no significant difference in the maximum insertion torque regarding the cortical bone thickness, but the insertion torque significantly increased for a dual-thread type miniscrew ($P < 0.0001$). Moreover, the maximum insertion torque from each cortical bone thickness was significantly different between the single-thread and dual-thread miniscrew designs ($P < 0.0001$). It was reported that the cortical bone thickness had little effect on the maximum insertion torque in a cylindrical-type miniscrew, but that with a taper-type miniscrew the maximum insertion torque significantly increased as the cortical bone thickness increased (24, 37), which is comparable to the results of the present study.

When the strain and insertion torque were compared according to the insertion depth, the strain of a single-thread type miniscrew decreased after reaching the highest strain and showed minor fluctuations for the remainder of the insertion. The strain of a dual-thread type miniscrew showed a pattern similar to that of a single-thread type miniscrew at the initial insertion, but the value of the strain increased gradually, reaching a second peak during the final insertion. Therefore, a dual-thread miniscrew may be efficient when a
screw is inserted into alveolar bone with lower bone density such as in the maxilla, but a single-thread miniscrew is recommended for cortical bone thicknesses of 2 mm or more and in high-density bone, such as in the mandible.

In addition, as this study considered only the initial stability of the miniscrew, which is affected by the miniscrew’s mechanical characteristics, experimental animal studies are required to better understand secondary stability, which includes osteointegration and bone remodelling in response to the strain. Finally, clinical trials to assess the long-term stability of different screw designs are essential for making it possible to select the most suitable miniscrew for clinical use.

**Conclusion**

Self-drilling dual-thread miniscrews provide better initial mechanical stability, but it may cause excessive strain that is over the physiological bone remodelling level at the bone-implant interface of thick cortical bone layers.

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**References**


