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Author(s)
Kuroda, S; Nishii, Y; Okano, S; Sueishi, K

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Stress distribution in the mini-screw and alveolar bone during orthodontic treatment: A finite element study analysis

Shuntaro Kuroda¹, Yasushi Nishii¹, Shigeru Okano², Kenji Sueishi¹

¹Department of Orthodontics, Tokyo Dental College
²Oral Science Research Center, Tokyo Dental College

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Corresponding Author:
Shuntaro Kuroda
Kuroda Dental Office
5-23-11 Honcho Koganei-shi, Tokyo Japan. 184-0004
Email: shuntarokuroda@gmail.com
Telephone: +81 (42) 384-3075
Fax: +81 (42) 384-3264
ABSTRACT

Objective: This study aimed to investigate the reason for high failure rate of mini-screws during orthodontic treatment. We hypothesised that decreasing the length of the mini-screw outside the bone relative to the length inside the bone (outside/inside length ratio) and equalising it to the tooth crown–root ratio would lead to increased stability of the mini-screw against lateral load when assessed using finite element analysis.

Methods: We analysed stress distribution of mini-screws in the cortical and trabecular bone and von Mises stress levels when a 2-N force was applied to the head of four mini-screws of 6, 8, 10 and 12 mm in length. The direction of the force was perpendicular to the major axis of screws. Results: Stress levels of screws in the cortical bone increased in proportion to the length of mini-screws outside the bone. The length of mini-screws inside the bone did not affect stress levels in the cortical bone. Conclusions: The results of this finite element analysis indicate that, to stabilise the mini-screw, controlling the screw length outside the bone is more important than controlling the outside/inside length ratio.

Keywords: Orthodontic mini-screw, Stress distribution, Finite element analysis, Outside/inside length ratio
Introduction

Use of mini-screws has become increasingly prevalent in the past decade because they confer a number of advantages when compared with conventional intra- and extra-oral anchorage reinforcement. However, despite several studies on mini-screws, only few standard evaluation methods have been established, and the reasons for the varying success of their use remain unclear (Reynders et al., 2008). In addition, few reports have been published on structural mechanics of mini-screws in relation to the bone.

Most published papers report a success rate of approximately 80% for mini-screws, including cases where mini-screws were mobile but effectively served as anchorage during the treatment period (Chaddad et al., 2008; Schatzle et al., 2009; Liu et al., 2011; Motoyoshi, 2011). However, the cause of mini-screw failure often remains unexplained. Mini-screw failure seems to be associated with conditions of insertion, and more importantly, the force of insertion with regard to magnitude and direction. Several studies and clinical reports have proposed that forces should remain below 200 gf (Miyawaki et al., 2003; Kuroda et al., 2007; Chatzigianni et al., 2011; Stanford, 2011; Pittman et al., 2013). According to one report, a force of 400 gf had no influence on the success rate (Janssen et al., 2008). With regard to the direction, Lee et al. reported the results of mini-screw traction in various directions after its insertion in various corresponding directions, stating that mini-screw insertion and traction should be performed at an appropriate angle for facilitating screw stabilisation, avoiding any direction that results in twisting or pulling of the mini-screw (Lee et al., 2013). Insertion conditions are determined by the magnitude and direction of the force and the location of insertion, and these include conditions of mini-screws and of the insertion site within the oral cavity. The latter closely depends on the treatment plan and the force system.
According to anatomical requirements, the location and depth of insertion must be considered to avoid injury to neighbouring structures such as roots of adjacent teeth, nerves, blood vessels and maxillary sinuses.

Cortical bone thickness (CBT) at the insertion location is an important factor in promoting initial stability of mini-screws (Moon et al., 2008; Qamaruddin et al., 2010; Motoyoshi, 2011). Properties of mini-screws itself primarily relate to their diameter and length, although they may also differ because of differences in their materials and designs (Wilmes et al., 2009; Motoyoshi, 2011).

Although the impact on the success rate is known for many parameters associated with the use of mini-screws, few published reports have focused on stress distribution of mini-screws within the bone complex. Moreover, stress distribution in the cortical or trabecular bone or at the cortical–trabecular bone interface varies between individual cases. Furthermore, stress distribution in mini-screws seems to vary depending on the ratio of the mini-screw length outside the bone to that inside the bone (outside/inside length ratio). The first study on mini-screw load transfer using finite element analysis was conducted in 2004 (Dalstra et al., 2004); stress distribution was evaluated following application of a 50-cN load on a mini-screw inserted into the bone, and results revealed that the stress was mostly distributed in the cortical bone.

The present study used finite element analysis based on the hypothesis that mini-screws would become more stable against a lateral load along with a decrease in the outside/inside length ratio. Our study uses an established finite element analysis method, contributes to the knowledge base and may be used to guide optimal clinical usage of mini-screws in orthodontics. Nienkemper et al. reported that finite element analysis was feasible for the simulation of an in vitro situation (Nienkemper et al., 2013).
**Materials and Methods**

On the computer, simulation models of the mini-screw and cortical and trabecular bone were created as described below.

First, models of the mini-screw and cortical and trabecular bone were created using a three-dimensional (3D) structure analysis program (Finite Element Stress Analysis System TRI/3D-BON, FEM, Ratoc System Engineering Co., Ltd., Tokyo). Mini-screw and bone parameters were set as follows (Figure 1):

Cortical bone: X, 12,000 μm; Y, 12,000 μm; Z, 12,000 μm (coordinates X 53-203, Y 53-203, Z 5-155)

Trabecular bone: X, 9,600 μm; Y, 9,600 μm; Z, 9,600 μm (coordinates X 68-188, Y 68-188, Z 20-140)

CBT: 1,200 μm (15 pixel × 80 μm, 1 pixel = 80 μm) (Kim et al., 2006; Baumgaertel et al., 2009)

Mini-screw diameter: 1,440 μm

Mini-screw length (4-8 = 12 mm, 4-4 = 8 mm, 2-8 = 10 mm, 2-4 = 6 mm)

Mini-screw shape: tip protruding at the site of insertion

The mini-screw was vertically implanted into the simulated cortical and trabecular bone model. Each model was named according to the screw length inside and outside the bone, e.g. the model with a 4-mm mini-screw portion exposed from the bone and an 8-mm portion inserted in the bone was tentatively called the ‘4-8 model.’ In this manner, four models (4-4, 4-8, 2-4 and 2-8 models) were created and subjected to finite element analysis as described below.

Raw bone material was defined by a computer after referring to data on bones in
the human body. The mini-screw raw material was assumed to be titanium. Young’s modulus and the Poisson coefficient for each material were determined as presented in Table 1 (Carter et al., 1978; Rho et al., 1993; Steinemann et al., 1996). The bone quality was determined on the basis of comparison with that of healthy adult orthodontic patients aged 18–35 years.

Borderline conditions were identified as summarised in Figure 1 and Table 2, immobilising planes 1, 2, 3 and 4. Thereafter, the load on mini-screws was programmed. Concentrated loading was performed with a 2-N load applied in the X direction (+). With screws 4-4 and 4-8, load was applied at a point with following coordinates: X, 119; Y, 128 and Z, 205. With screws 2-4 and 2-8, load was applied at a point with following coordinates: X, 119; Y, 128 and Z, 180.

On cross-sectional views of each model, a 2-N force (tractive force) directed to the right was vertically applied to the mini-screw at point A of the mini-screw head (Figure 2). The resulting stress distribution in the mini-screw and cortical and trabecular bone in each model was subjected to finite element analysis. The mini-screw form was designed to be as simple as possible to enable successful application of the study data to most commercially available mini-screws. The screw thread, known to have little impact on cortical bone strain (Lin et al., 2010), was not adopted as a variable in this finite element study model.

For each stress value point, we used TRI/3D-FEM to calculate the von Mises stress distribution. Stress levels were compared among several selected points. Figure 2 presents the location of each point.

The method for presenting the results of finite element analysis is discussed below. Figures presenting the mean principal stress (figures coloured red and blue;
cross-sectional and top-surface views) were prepared as follows:

A contour figure of stress was prepared using the analysis result-presenting function of TRI/3D-FEM.

The cross section and cortical bone surface were presented using the 3-D display function of TRI/3D-BON. The colour bar for the contour figure proportionally represents stress levels from minimum (gradation 1:blue) to maximum (gradation 255:red).

A contour figure was prepared using Excel 2007 as follows:

From the calculated stress data for the entire region, stress levels in a selected area were calculated.

Von Mises stress was calculated from X, Y and Z data.

A pivot table was prepared by extracting data on three variables (X, Y and von Mises stress).

A contour figure was prepared from the pivot table using the contour figure preparing function of Excel 2007.

Stress distribution in mini-screws was graphically represented as follows.

A contour figure of stress was prepared using the analysis result-presenting function of TRI/3D-FEM.

The mini-screw and cortical and trabecular bone were isolated using the inter-image calculation and 3D-display functions of TRI/3D-BON.

A figure of stress distribution in each mini-screw was individually prepared.

Stress distribution in the bone without a mini-screw was graphically represented as mentioned below.

a) Steps (1) and (2) were performed as previously described for the preparation of a
figure of stress distribution in mini-screws.

b) A stress distribution figure was prepared by combining data other than those related to the mini-screw.

**Results**

Table 3 summarises the von Mises stress distribution at all main points in cross sections.

In 4-4, 4-8, 2-4 and 2-8 models, von Mises stress at point A was the highest. In addition, this stress was symmetrically distributed on both tensile and compression sides of the mini-screw. In 4-4 and 2-4 models, this stress was distributed over the entire mini-screw without a single point of excessive stress. On comparing the stress at points DS and DB, we observed that the stress on the cortical bone was decreased to 50%–60% of the stress on the mini-screw. Similarly, the stress at point GB was decreased to 4% of the stress at point GS.

Figures 3 and 4 indicate that the stress was distributed along the interface between the cortical and trabecular bone as well as along portions distal from the mini-screw. Figure 5 indicates that at the cortical bone surface level, the rate of decrease in stress was lower inside the mini-screw than inside the bone. In addition, the von Mises stress at point E was the lowest among all models.

Figure 6 illustrates stress distribution on the contact surface between the mini-screw and bone. In 4-8 and 4-4 models, more areas are coloured red, indicating greater stress distribution within the mini-screw. Red areas are distributed both inside the cortical bone and above the level of the surface, whereas only a small amount of stress can be observed in the trabecular bone. Notably, in the 4-4 model, high stress is
distributed across the mini-screw.

Figure 7 illustrates stress distribution on the contact surface between the bone and mini-screw. Stress sharply decreased as the distance from the margin increased, and stress is more extensively distributed at the cortical bone surface level in 4-8 and 4-4 models compared with that in 2-4 and 2-8 models. The number of red-coloured areas is greater in the marginal area in 4-8 and 4-4 models than in 2-4 and 2-8 models. However, the distribution of yellow-coloured areas in the bone wall is more extensive in the 4-4 model than in other models.

**Discussion**

The concept of skeletal anchorage following which temporary anchorage devices (TADs) of various designs were developed was first proposed to provide anchorage in adult orthodontic treatment (Creekmore et al., 1983). Thereafter, a report on TADs began to be extensively used in orthodontic treatment (Kanomi, 1997). TADs, known as mini-screws, are advantageous as they do not require complex manipulation or surgery and are easy to remove once their purpose is fulfilled. In addition, concentrated loading is possible immediately after surgical insertion of a mini-screw.

The present study makes some assumptions. It is based on adult orthodontics, wherein the first premolar has been extracted, and a mini-screw is embedded in the alveolar bone between the maxillary second premolar and first molar for use as anchorage during canine distal drive and anterior retraction. Thereafter, we performed finite element analysis of stress distribution on the mini-screw, alveolar bone (cortical bone and trabecular bone) as well as the mini-screw–bone complex. While designing models for analysis, care was taken so that advantages of finite element analysis could
be adequately utilised, while avoiding a loss of general versatility of models, which may result because of excessive concern with details. The number of variables adopted was minimised, resulting in a model with a simple cubic shape, and the model surface resembled the cortical bone surface. Models were produced assuming that the alveolar bone, which contained the alveolar socket (cortical portion) and the mini-screw, were embedded between roots of teeth.

As previously mentioned, we selected four screw configurations for finite element analysis (4-4, 4-8, 2-4 and 2-8) to assess stress distribution on the bone and mini-screw over four different ratios. These corresponded to ratios of the mini-screw length outside the bone to that inside the bone (outside/inside ratio) of 1:1, 1:2, 1:2 (changing the length outside the bone) and 1:4. If the length outside the bone was increased, the stress obviously became concentrated at the neck of the mini-screw. However, it is clinically valid to analyse consequences of altering the length inside the bone. By examining stress levels of each analysed point in this study, we identified no significant difference between all points. On the basis of this finding, it is reasonable to expect that results would be similar even if the length outside or inside the bone was increased.

In all tested models, the margin close to the cortical bone surface revealed the densest stress distribution. The contour figure (Figure 5) indicates that this area was exposed to the highest stress. Moreover, stress was extensively distributed in the mini-screw portion inserted within the cortical bone. The portion inserted within the trabecular bone appears as a dull yellow area, indicating a rapid decrease in stress. These findings indicate that the mini-screw is supported by cortical bone. Adequate mechanical interlocking between the mini-screw and cortical bone showed the greatest impact on mini-screw stability (Miyawaki et al., 2003; Motoyoshi, 2011). Furthermore,
stress distributed in the mini-screw portion outside the bone is higher compared with that in the mini-screw portion within the trabecular bone. This difference may be because the mini-screw portion outside the bone is closer to the action point or because the elastic modulus of the trabecular bone is lower compared with that of the cortical bone, thereby failing to show high stress levels.

At the mini-screw margin closer to the cortical bone surface level, the mini-screw side was represented by point DS, and the bone side was represented by point DB. With an increase in the mini-screw length outside the bone, the von Mises stress at point DS increased. This change was determined by the mini-screw length outside the bone alone. The von Mises stress at point DB seems to reflect the load on the surrounding bone, as determined by the mini-screw length outside the bone or the outside/inside length ratio. This finding indicates that the mini-screw length outside the bone should be controlled for appropriate stress distribution in the mini-screw, and that the outside/inside length ratio should be controlled for appropriate stress distribution in the bone.

In the present study, both mini-screw width (diameter) and CBT were kept constant. Under these conditions, the von Mises stress inside the mini-screw decreased, and the mini-screw became more stable because the mini-screw length outside the bone was decreased. When the length outside the bone was kept constant, the von Mises stress at the cortical bone surface minimally varied, even when the length inside the bone was increased. With regard to the length inside the bone, a few studies have suggested that a depth of insertion of at least 5–6 mm is required, and a deeper placement is required at sites with poor bone quality (Creekmore et al., 1983; Wiechmann et al., 2007; Kuroda et al., 2007).

The cross-sectional view of stress distribution at point E indicates that the von
Mises stress is lower if the mini-screw length outside the bone is decreased. Furthermore, as indicated by Figure 7, the von Mises stress is the lowest at the cortical bone surface level. This stable point may be viewed as the centre of rotation of the mini-screw.

Point G serves as the point of contact between the mini-screw and the cortical–trabecular bone interface. At this point, three different materials interact, resulting in stress distribution patterns different from that at other points. At point G, the side closest to the mini-screw is termed point GS. At point GS, the von Mises stress is greater when the mini-screw length outside the bone is 4 mm compared with when this length is 2 mm. In addition, the von Mises stress at point GS correlates with the stress at the mini-screw margin (point D) closest to the cortical bone surface. If the stress at this point is high, it will be distributed, probably resulting in high stress at point GS. Concurrently, if the mini-screw length outside the bone is kept constant, the von Mises stress at point GS increases with an increase in the mini-screw length inside the bone. Therefore, it seems likely that with an increase in the length inside the bone, there is a relative decrease in the outside/inside length ratio, thereby resulting in greater von Mises stress at point GS (probably reflecting the ratio of the inside length of the mini-screw that was supported by cortical bone to the inside length surrounded by trabecular bone), whereas the von Mises stress at point GB is only approximately 4% of the stress at point GS (Table 3). This indicates that there is barely any stress distributed on the bone side at this point.

As presented in Figure 3, the von Mises stress on the cortical bone surface increases as the distance to the mini-screw decreases. However, at the cortical–trabecular bone interface, stress is also distributed at points distant from the mini-screw.
We assume that point E serves as the centre of mini-screw rotation. Under this assumption, points F and G are on the compression side. At points near the mini-screw, the compression stress is offset by the tensile stress from point D, resulting in distribution of low compression stress. As the distance from the mini-screw increases, the residual stress from point D is probably widely distributed along the interface within the cortical bone.

The von Mises stress at the apex (point L) was as low as 0.06 MPa, which is likely to have little impact on the bone or mini-screw (Table 3).

Finite element analysis revealed that factors affecting stress distribution varied among individual points, i.e. some points were affected by the mini-screw length outside the bone, some by the length inside the bone and some by the outside/inside length ratio.

We hypothesised that a smaller outside/inside length ratio would lead to increased stability of the mini-screw against lateral load when assessed using finite element analysis. However, we observed that mini-screw stability was not affected by the outside/inside length ratio. Therefore, the mini-screw is unlikely to become unstable even when the higher-risk mini-screw design (considerably of greater length inside the bone) is not adopted. The mini-screw is primarily supported by cortical bone, and the part surrounded by trabecular bone did not significantly influence mini-screw stability, which is enhanced by controlling its length outside the bone rather than decreasing the outside/inside length ratio.
Conclusion:

1. Stress due to traction force around the mini-screw was concentrated on the cortical bone (mini-screw neck) and decreased sharply with an increase in distance from the mini-screw.

2. Stress at the cortical bone surface was approximately double that at the cortical–trabecular bone interface.

3. Stress was affected largely by the length of the mini-screw outside the bone, with the stress around the mini-screw increasing in proportion to its length.

4. Under these finite element analysis conditions, a decrease in the outside/inside length ratio of the mini-screw probably does not result in destruction of the bone or displacement or deformation of the mini-screw; in addition, it may not affect stability.
**Ethical approval:** Ethical approval was not required for this study.

**Informed consent:** Patient consent was not obtained

**Competing interests:** The authors have no competing interest to declare.

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References


Lee J, Kim JY, Choi YJ, Kim KH, Chung CJ. Effects of placement angle and direction


Table 1: Properties of the constituent materials

Material properties of constituent materials

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<th>Material</th>
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mini-screw: Steinemann et al., 1996

cortical bone: Carter et al., 1978

trabecular bone: Rho et al., 1993
### Table 2: Borderline conditions of the finite element study model

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(MPa)

Table 3: The von Mises stress distribution at each point
Figure legends

Figure 1: Finite element model comprising the mini-screw and alveolar bone
A mini-screw (1.44 mm in diameter) was vertically implanted into a cubic structure (simulated cortical/trabecular bone).

Figure 2: Arrangement of points in the 4-8 model
A mini-screw (portion above the bone: 4 mm in length and portion inside the bone: 8 mm in length) implanted into a simulated bone. The dark blue area indicates the cortical bone.

Figure 3: Cross-sectional images of stress distribution figures (stress at each point; coloured stress distribution graph; von Mises stress distribution)
A symmetrical stress distribution is visible in the main portion of the mini-screw. Stress is concentrated at the neck of the mini-screw. Stress is distributed up to the mini-screw apex when the mini-screw length inside the bone is 4 mm.

Figure 4: Top view of coloured images of stress distribution at the cortical–trabecular bone interface
Stress is distributed even at points distant from the mini-screw.

Figure 5: Contour figures for stress distribution (von Mises stress) at the surface level (MPa)
Stress becomes highest at the mini-screw margin. Stress within the bone sharply
decreases and further decreases towards the mini-screw centre.

Figure 6: Stress distribution at the mini-screw surface contacting the bone on the tensile side
High stress distribution (dark red area) is visible in the area in contact with the bone. The high-stress area is wider if the mini-screw length above the bone is 4 mm.

Figure 7: Stress distribution at the bone surface contacting the mini-screw on the tensile side
In each model, high stress distribution is observed at the cortical bone surface level. The stress inside the bone was lower than that at the cortical bone surface.

Table Legends
Table 1: Properties of constituent materials
Table 2: Borderline conditions of the finite element study model
Table 3: The von Mises stress distribution at each point
Figure 1  Finite element model consisting of mini-screw and alveolar bone
Arrangement of points in model 4-8

Figure 2: Arrangement of points in model 4-8
Figure 3: Cross-sectional images of stress distribution figures (stress at each point; colored stress distribution graph; von Mises stress)
Figure 4: Colored images of stress distribution at the cortical–trabecular bone interface, when viewed from the top
Figure 5: Contour figures for stress distribution (von Mises stress) at the surface level (MPa)
Figure 6: Stress distribution at the mini-screw surface contacting the bone on the tensile side
Figure 7: Stress distribution at the bone surface contacting the mini-screw on the tensile