Mini-implant loosening: 3D analysis using the finite element method

Allahyar Geramy, DDS, MSc¹
Jean Marc Retrouvey, DMD, MSc²
Reza Jelodar, DDS, MSc³
Hasan Salehi, DDS, MSc⁴

Aim: Mini-implants are a relatively new device for absolute anchorage control in orthodontics. Their failure due to loosening is a multifactorial problem. Improper positioning of mini-implants with different diameters is evaluated in this study via the finite element method. Methods: Twelve 3D finite element models of a mandibular posterior segment were designed and included the first molar, a mini-implant, the periodontal ligament, and spongy and cortical bone. They were similar except for the mini-implant position and diameter (1.3, 1.6, and 2.2 mm). A vertical force of 300 N was applied to the occlusal molar surface. The von Mises stress and energy produced by the applied occlusal forces were assessed in the mini-implant and bone. Results: The stress findings were between 15.284 and 359.77 MPa for the mini-implants based on their diameters and locations. The mini-implant energy findings were between 0.00084 and 0.258 mJ. These ranges for bone stress and energy changes were 17.611 and 129.45 MPa and 0.296 and 1.575 mJ, respectively. Conclusion: A decrease in the distance between the mini-implant and tooth root has a direct effect on different parameters to explain mini-implant loosening. Orthodontics (CHIC) 2012;13:e51–e57.

Key words: absolute anchorage, finite element method, mini-implant loosening

Achorage control is one of the most important aspects of orthodontic biomechanics. Poor anchorage control during tooth movement may increase treatment time and lead to unfavorable results. Mini-implants are used for absolute anchorage control in orthodontic treatment. The success rate for mini-implants has been reported to be 87.5% to 100%.¹⁻³

A mini-implant’s stability is correlated to the degree of inflammation,⁴ local irritation,⁵ excessive orthodontic load,¹ quality and quantity of cortical bone,⁶ design and shape of screw thread,⁷,⁸ and mini-implant proximity with adjacent tooth roots.⁹⁻¹¹ Other factors such as patient age, insertion site of the mini-implant, craniofacial pattern,¹⁰,¹²,¹³ and the amount of the implant placement torque (IPT) have also been assessed.¹⁴

Shan et al.¹⁵ showed that implanting angles have much more influence on stress distribution and that the stress is located primarily at the neck of the mini-implant. Also, a decreased implant angle and a reduced angle between the load line and implant long axis can decrease peak stress.¹⁵
One of the most important factors that affects the success rate is cortical bone thickness. Motoyoshi et al. explained that the success rate decreases with reduced cortical bone thickness beyond 1 mm.

In another study, Motoyoshi et al. found that 2 mm bone thickness is more susceptible for failure than 1 or 3 mm and implant proximity with adjacent tooth roots was shown to be one of the influencing factors for increasing stress beyond 140 MPa. Attached gingiva is another important factor for mini-implant success. Cheng et al. found that one of the reasons for the lower success of mini-implants in the mandible is narrow keratinized gingiva.

Finite element method (FEM) is a numerical analysis to find an approximate solution to a complex problem. It was first introduced in the aerospace industry. This method has proven its efficiencies in different fields. Three-dimensional (3D) FEM is a powerful tool used to examine the complex mechanical behaviors of dental structures. Its efficiency in designing, analyzing, and finding answers to dental biomechanical problems has been proven.

The main goal of this study was to analyze the effect of mini-implant diameter and position in relation to the tooth root on its stability based on a von Mises stress and energy approach.

**METHODS**

Twelve 3D finite element models were designed of a mandibular posterior segment and included the first molar (based on the mean dimensions) and supporting structures (Fig 1). A problem arose when trying to make a standard situation for contact between the mini-implant and root surface. It is known that a small difference in the contact area can directly affect the findings. Due to the curved surface of the root, it was almost impossible to define the same penetration depths in different mini-implant diameters. The root was flattened to provide a practical situation for its contact with the mini-implant. (This was a modification to the real root form design.) Each model consisted of a spongy core surrounded by a 1-mm cortical layer. A simplified 0.25-mm periodontal ligament (PDL) layer was modeled based on the root-form geometry of the molar. The 3D models were the same except for the mini-implant diameter and position. Position A was defined as a close contact and penetration of mini-implant screw threads and body in the root surface in such a way that half of the mini-implant diameter is penetrated into root surface from mesial side, making a 32-degree angle to the horizontal plane (from a mesial view). Position B was defined as when the mini-implant threads penetrated into the root surface, but the mini-implant body was not in contact. Position C was when the mini-implant entered the PDL without any contact with the root surface (Fig 2). Position D was defined as the mini-implant embedding in the bone with a minimum of bone thickness with the root socket.

SolidWorks 2010 was selected for the modeling phase. The next phase was to transfer the models for calculation to the ANSYS Workbench 12.1 (ANSYS). All the vital tissues were presumed elastic, homogeneous, and isotropic. Corresponding elastic properties such as the Young modulus and Poisson ratio were applied (Table 1). Bonded contacts made it possible to define the contacts between the tooth, its PDL, the spongy and cortical bone, and the mini-implants with bone tissue types. All nodes at the mesial and distal extremes of the models were restrained so that all rigid body motions were prevented. A vertical force of 300 N was applied at occlusal surface of molar. The mini-implant was not loaded.

Different approaches were selected to study the effects of mini-implant position and diameter, which were to assess the maximum von Mises stress in and the energy transferred to the mini-implant and bone.
RESULTS

The numeric data are divided according to the involved tissues (Table 2).

Bone

**Bone stress (Fig 3).** The findings for the three mini-implant diameters in terms of bone stress are as follows:

1. **1.3 mm diameter:** The maximum of von Mises stress detected in the bone starts with 126 MPa in position A and increased to 129.45 MPa in position B and decreased when moving away and staying in the PDL (21.201 MPa). (position C). The lowest finding (18.09 MPa) was in position D.
2. **1.6 mm diameter:** The bone stress in position A was the highest (98.86 MPa) and decreased to 66.772 MPa in position B. The decreasing trend continued in position C (20.44 MPa) and position D (17.61 MPa).
3. **2.2 mm diameter:** Findings start with 81.91 MPa in position A and decreased to 65.91 MPa in position B. Bone stress in position C was 19.57 MPa, and the lowest finding was 18.26 MPa for the farthest position from the mini-implant to the root surface (position D).
**Bone energy (Fig 4).** The findings for the three mini-implant diameters in terms of bone energy are as follows:

1. **1.3 mm diameter:** The energy transfer to the mini-implant starts with 1,243.6 μJ in position A, 1,063.7 μJ in position B, 453.21 μJ in position C, and 298.47 μJ in position D.
2. **1.6 mm diameter:** The energy transferred to the mini-implant starts with 1,157.5 μJ in position A, 894.84 μJ in position B, 299.2 μJ in position C, and 297.58 μJ in position D.
3. **2.2 mm diameter:** The energy transferred to the mini-implant starts with 1,056.9 μJ in position A, 852.84 μJ in position B, 291.48 μJ in position C, and 296.08 μJ in position D.

**Mini-implant**

**Mini-implant stress (Fig 5).** The findings for the three mini-implant diameters in terms of mini-implant stress are as follows:

1. **1.3 mm diameter:** The von Mises stress detected in the mini-implant starts with 359.77 MPa in position A, 607.6 MPa in position B, and 45.32 MPa in position C. The lowest finding (16.098 MPa) was in position D.
2. **1.6 mm diameter**: The findings in position A were 322 MPa and increased to 448.84 MPa in position B. The findings decreased in positions C (22.59 MPa) and D (16.18 MPa).

3. **2.2 mm diameter**: Findings started with 285.75 MPa in position A and increased to 398.32 MPa in position B. It was 17.75 MPa in position C and 15.284 MPa for position D.

**Mini-implant energy (Fig 6)**. The findings for the three mini-implant diameters in terms of mini-implant energy are as follows:

1. **1.3 mm diameter**: The mean energy produced in the mini-implant starts with 253.42 μJ in position A and decreased to 235.4 μJ in position B, 0.86 μJ in position C, and 0.84 μJ in position D.

2. **1.6 mm diameter**: The energy transferred to the mini-implant screw starts with 254.39 μJ in position A and decreased to 246.99 μJ in position B. In position C, it was 1.341 μJ, and in position D, 1.135 μJ was found.

3. **2.2 mm diameter**: The energy transferred to the mini-implants starts with 258.02 μJ in position A, 273.77 μJ in position B, 2.248 μJ in position C, and 1.73 μJ in position D.
DISCUSSION

Mini-implants are assumed to be a source of stable anchorage in orthodontics. Different studies have been published on their reaction to the applied forces. Different aspects of mini-implant insertion have been assessed so clinicians can use them as a guide.\textsuperscript{13,14,17}

FEM is used to evaluate parameters of interest in a complex structure. It has been shown to be a cost-effective and valid method of determining the behavior of structures under load. This study tried to evaluate the phenomenon of mini-implant loosening based on its position and diameter.

Increased bone stress (11\% to 20\%) and mini-implant stress (16\% to 196\%) was shown in the mini-implant when entering the PDL space. This increment was higher in the 1.3-mm diameter mini-implant. It can be interpreted by the reduced surface and constant force, which is noticed in a 1.3-mm diameter mini-implant. This finding is similar to Motoyoshi et al.\textsuperscript{10}

Asscherickx et al\textsuperscript{11} found that mini-implant proximity with adjacent tooth roots may be a major risk factor for mini-implant failure. The transfer of biting force to the mini-implant was suggested to be the reason of this failure, which is in accordance with our study.

They could not find a minimum distance between the root and the mini screw to be considered as a factor of failure. In that study, entering PDL and contacting the root surface was shown to increase stress and energy to the mini-implant. In turn, a distance less than 1 mm between marginal bone and mini-implant was shown to be a factor of increased failure.

Kuroda et al\textsuperscript{9} explained that the proximity of the mini-implant with the tooth root was a factor of failure, especially in the mandible.

A gradual increase in the bone stress findings was shown to exist moving from position D to A. This was 4.65 (2.2 mm diameter) to 7.15 times (1.3 mm diameter) of bone stress in position A compared with position D.

When the mini-implant threads reached the root surface (position B), the bone stress increase was between 3.74 times in the 2.2 mm diameter and 7.35 times for the 1.3-mm diameter mini-implant. The bone energy findings followed almost the same pattern but with less slope—between 2.88 and 3.59 times.

The highest failure risk based on the mini-implant stress and bone stress was shown to be in 1.3-mm diameter mini-implants contacting the root surface by its threads.

Between 18 and 24 times of stress increase was shown in the mini screw when embedding (50\% of its diameter) into the root surface with the root surface which was in inverse relation with the mini-implant diameter. These findings showed a decrease when compared with a situation of thread penetration to the root surface (between 26 and > 39 times of stress). In this way, it is shown that mini-implants reaching teeth roots are more prone to loosening than ones penetrating farther into the root.

Energy is transferred to a body when work is done on it. In this way, it can be said that work is the energy in transfer.\textsuperscript{25} In this way, work and energy are considered to be the same (they have the same units).

The work done in loading the specimen equals its increase in strain energy.\textsuperscript{26} Energy analysis when joined with other findings can provide a clearer view of the events which has not been done in previous studies. A higher chance of mini-implant loosening can be interpreted by evaluating the energy changes with the reduction of its distance to the root socket.

The bone and mini-implant energy change was up to 53\% and 167\%, respectively, when entering the PDL space. These energy changes were 273 to 326 times (in the mini-implant) and 2.88 to 3.59 times (in the bone) when coming in contact with root surface. Adding these energy modifications and the stress changes to-
geramy et al.

References


