Effects of washer on the stress distribution of mini-implant
A finite element analysis

Hyoung-Jun Jang[a]; Soon-Yong Kwon[b]; Seong-Hun Kim[c]; Young-Guk Park[d]; Su-Jung Kim[e]

ABSTRACT
Objective: To investigate the biomechanical effects of 'washer' designed for improving mini-implant stability.
Materials and Methods: Four three-dimensional finite element models of the mini-implant and surrounding bone were constructed with washers in different spike lengths (1.5 mm, 2.0 mm, and 2.5 mm). The force was applied in two directions (45° and 90°). The stress distribution on surrounding bone and the displacement of the mini-implant were analyzed. Plots of tensile stress, compression stress, and displacement were calculated, and maximum values in each category were analyzed.
Results: The stress distribution was different between the models with washer and without washer. However, no remarkable differences in stress distribution were observed among the models with washer, regardless of spike length. A significantly greater displacement value was observed in the model without washer compared to the models with washer, but no notable difference in displacement value was found among the models with washer. The plots of the displacement distribution of the models with washer presented notable pattern differences as compared with that of the model without washer.
Conclusion: With the use of the washer, a more homogeneous distribution of bone stress and less displacement of the mini-implant can be achieved. (*Angle Orthod.* 2012;82:137–144.)

KEY WORDS: Finite element analysis; Mini-implant; Stability; Washer

INTRODUCTION

In contemporary orthodontic treatment, mini-implants are used for stationary anchorage, eliminating reciprocal tooth movement. Thus, mini-implants allow clinicians to overcome the limitations of conventional orthodontic treatment. In addition, orthodontic mechanics have become simpler and the treatment period has been reduced with the aid of mini-implants. Mini-implants are also beneficial to patients because they minimize discomfort.

However, despite these great advantages, many clinicians have experienced loosening of mini-implants. Miyawaki et al.,[1] Cheng et al.,[2] Kuroda et al.,[3] and Lim et al.[4] reported mini-implant success rates of 84%, 89%, 80%, and 83.6%, respectively; the corresponding failure rate of 10–20% cannot be disregarded. For this reason, numerous researchers[2,4,5] have studied the factors involved in the failure of mini-implants. One principal factor that influences the stability of mini-implants is stress from loading. Crupi et al.[6] reported that the effects of overloading include the accumulation of damage that can cause fatigue failure of bones. According to Huiskes and Nunamaker,[7] high peak stress at the interface can cause loosening of mini-implants and bone absorption.

Therefore, in order to overcome these problems, orthodontic mini-implants should be designed so that the peak bone stress due to orthodontic force is minimized. By increasing the interface between the mini-implant and the bone, peak bone stress is decreased. Previous studies reported better stress

[a] Graduate student, Graduate School of Dentistry, Kyung Hee University, Seoul, South Korea.
[b] Private practice, Central Orthodontic Clinic, Seoul, South Korea.
[c] Associate professor, Department of Orthodontics, Kyung Hee University, Seoul, South Korea.
[d] Professor, Department of Orthodontics, Kyung Hee University, Seoul, South Korea.
[e] Assistant professor, Department of Orthodontics, Kyung Hee University, Seoul, South Korea.
Corresponding author: Dr Su-Jung Kim, Department of Orthodontics, Kyung Hee University, 1, Hoegi-dong, Dongdaemun-goo, Seoul, Korea
(e-mail: ksj113@khu.ac.kr)

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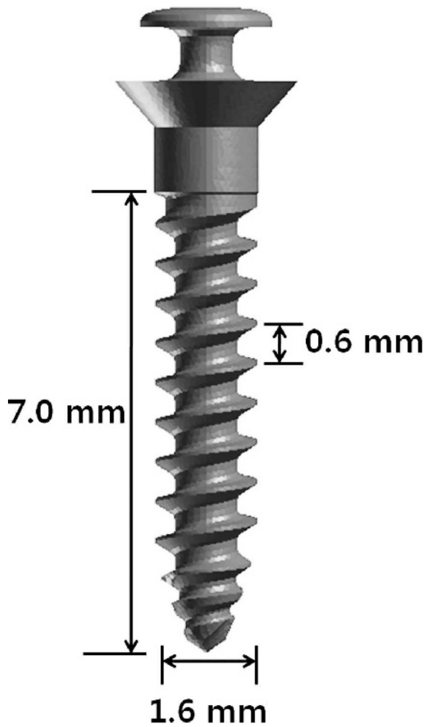

Figure 1. Mini-implant designed in this study.

distribution when the diameter,[8–10] the height of the thread,[11] and the length[2] of the mini-implant are increased and when the pitch[12] is decreased. However, there are limitations involved with overcoming the failures by merely increasing the interface.

In this study, an additional structure called a washer was combined with the mini-implant in an attempt to improve the stability by modifying the force system, rather than by increasing the interface. A washer, which is a disk-shaped thin plate with a hole, is normally used to distribute the load of a threaded fastener, such as a screw or a nut. The washer used in this study represented a modified form of the original washer, with the addition of spikes to render the washer effective in soft tissue.

The object of the study was to investigate the biomechanical effects of the washer designed for improving mini-implant stability. The stress distribution on surrounding bone and the displacement of the mini-implant were analyzed using finite element analysis to evaluate the efficacy of the washer.

MATERIALS AND METHODS

The mini-implant surfaces were reconstructed on the basis of CAD data related to the Zin-E screw® (Jin-Biomed, Seoul, Korea) in IGES format by means of the FE program system PAM-MEDYSA® V 2010 (ESI Co, France) (Figure 1). The threaded part of the

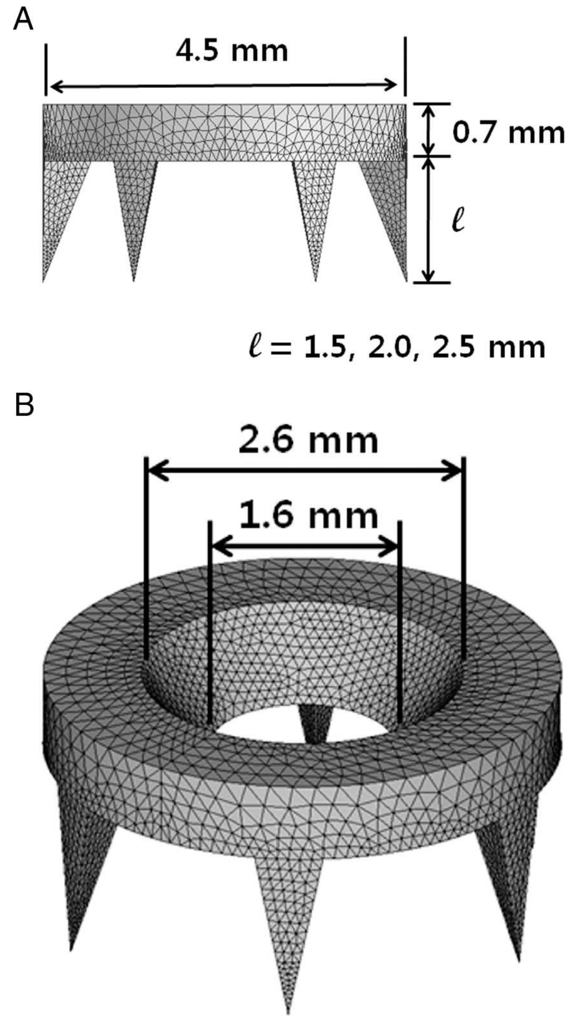

Figure 2. Finite element model of washer.

mini-implant was 7 mm long and cylindrical in shape. The diameter of the mini-implant was 1.6 mm, and the pitch of thread-ridge was 0.6 mm. The neck design had to be modified in order to facilitate a proper combination with the washer.

The round plate of the washer was 4.5 mm in diameter and 0.7 mm in thickness, and six spikes were attached to the bottom side of the washer. The washer had a tapered hole in the center, with top and bottom radii of 2.6 mm and 1.6 mm, respectively. The tapered hole of the washer was exactly fitted to the neck of the mini-implant. To verify the influence of spike length on the initial stability, the spikes were designed with lengths of 1.5 mm, 2 mm, and 2.5 mm (Figure 2). The surfaces of the mini-implant and the washer were constructed as smooth surfaces. The mini-implant and the washer were assumed to be made of titanium alloy (Grade IV).

Bone structure was arbitrarily designed to be represented by a 10-mm cube, which was large enough to assess the stresses surrounding the

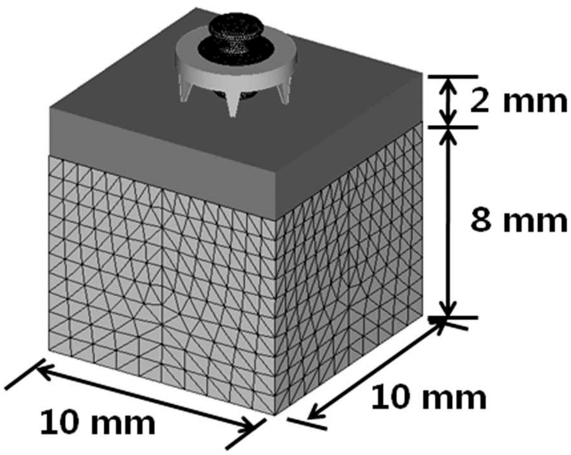

Figure 3. A complete finite element model.

mini-implant, according to the pilot study. The cortical bone thickness was 2 mm, which is the mean value of upper buccal cortical bone thickness.[12,13] The remaining 8 mm was designed to be cancellous bone.

The mini-implant model with the washer was inserted into the FE geometry of the bone structure. The spike was embedded into the cortical bone, leaving 1.0 mm of full length in consideration of the soft tissue thickness. The mini-implant without the washer was inserted into the bone at the same depth as the mini-implant in the other models. To reproduce a condition before osseointegration, gap elements were provided between the mini-implant and the bone elements, and the friction coefficient was fixed to 0 (as the contact condition between the mini-implant and the washer). Numerous applications of finite element analysis (FEA) have provided remarkable differences in terms of the results by setting the boundary conditions as "fixed bond," "slip contact," or "contact with no friction." However, these studies are insufficient for providing guidelines on designing the most realistic interface boundary conditions. Therefore, this study set the boundary conditions according to the study of Motoyoshi et al.,[12] which also aimed to observe the initial stability of the mini-implant before osseointegration. Thus, a complete model of the mini-implant, together with the washer and the bone, was created (Figure 3). Model A was designed without the washer, and models B, C, and D had washers (spike length set to 1.5 mm, 2.0 mm, and 2.5 mm, respectively). A traction force of 2 N was applied in two directions, namely, 90° and 45° to the longitudinal axis of the mini-implant (Figure 4).

Nodes surrounding the bone elements were restricted to 3 degrees of freedom. All materials used in the models were considered to be isotropic, homogeneous, and linearly elastic. The total number of nodes and elements for the models varied from 212,131 to

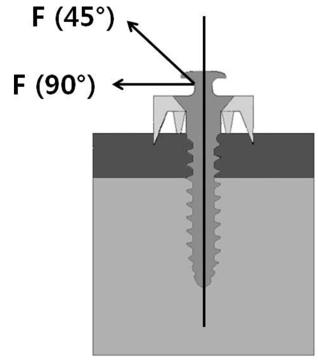

Figure 4. A traction force of 2 N was applied in two directions.

327,122. The material properties were taken from the literature, as shown in Table 1.[14,15] Assessments of stress distribution on the bone elements were performed using maximum and minimum principal stress analysis. The displacements of the mini-implants were analyzed to evaluate their stability.

According to the authors' institution, this study did not require approval by their institutional review board.

RESULTS

The stress distributions on the bone are represented by color-coded images (Figures 5 through 7). In order to compare the stress values, the figures are equally scaled. The tensile stress values exceeding 2 MPa are encoded in red, and the maximum compression stress values exceeding 2 MPa are encoded in blue. The tensile stress was analyzed in positive values and the compression stress in negative values, but in further analysis, these values were considered in absolute values. Displacement of the mini-implant is also shown in the color-coded images, and 0.9 μm or more of displacement is encoded in red. Through the pilot study and the study of Motoyoshi et al.,[12] a scale was set that renders the results of this study most appropriately. The maximum values of tensile and compression stress and the displacement magnitudes are listed in Tables 2 and 3.

Maximum Principal Stress

Maximum principal stress was used to analyze the tensile stress applied to the bone elements. When the force was applied at 90° to the mini-implant head, a remarkable difference was observed between the model

Table 1. Material Properties of Constituent Materials

Material	Young's Modulus, GPa	Poisson's Ratio	Mass Density, g/cm³
Titanium alloy	110,000	0.3	4.5
Cortical bone	13,700	0.3	1.8
Cancellous bone	300	0.3	0.8

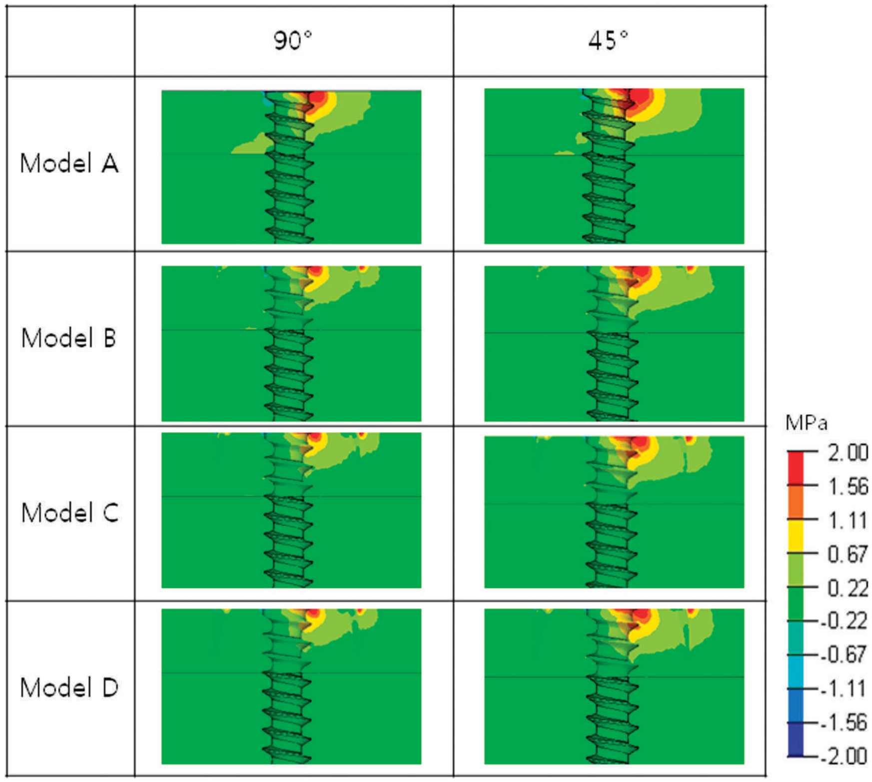

Figure 5. Tensile stress distribution on bone elements.

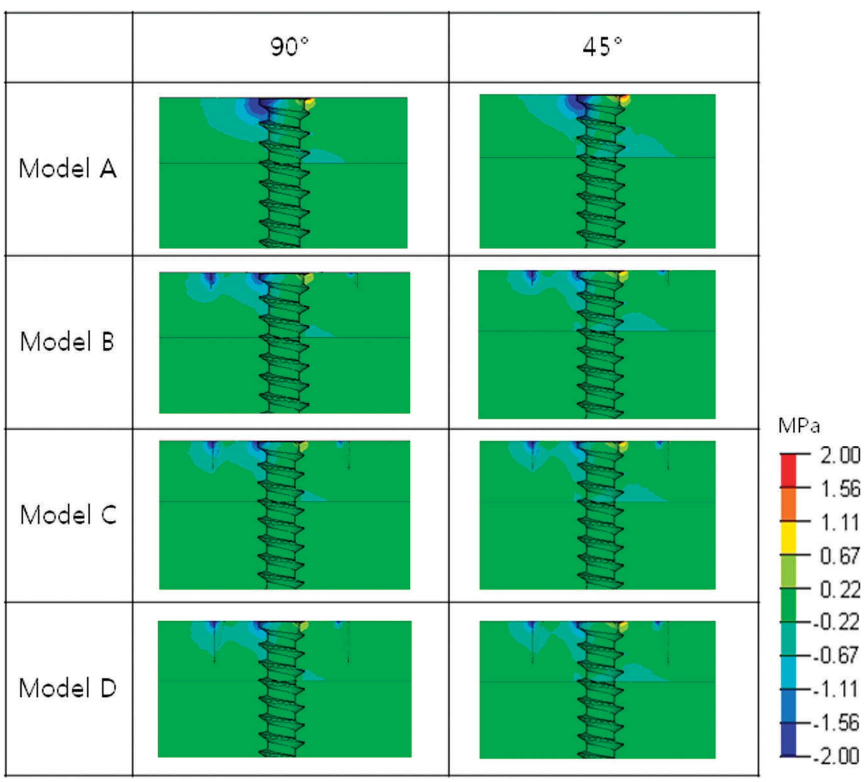

Figure 6. Compression stress distribution on bone elements.

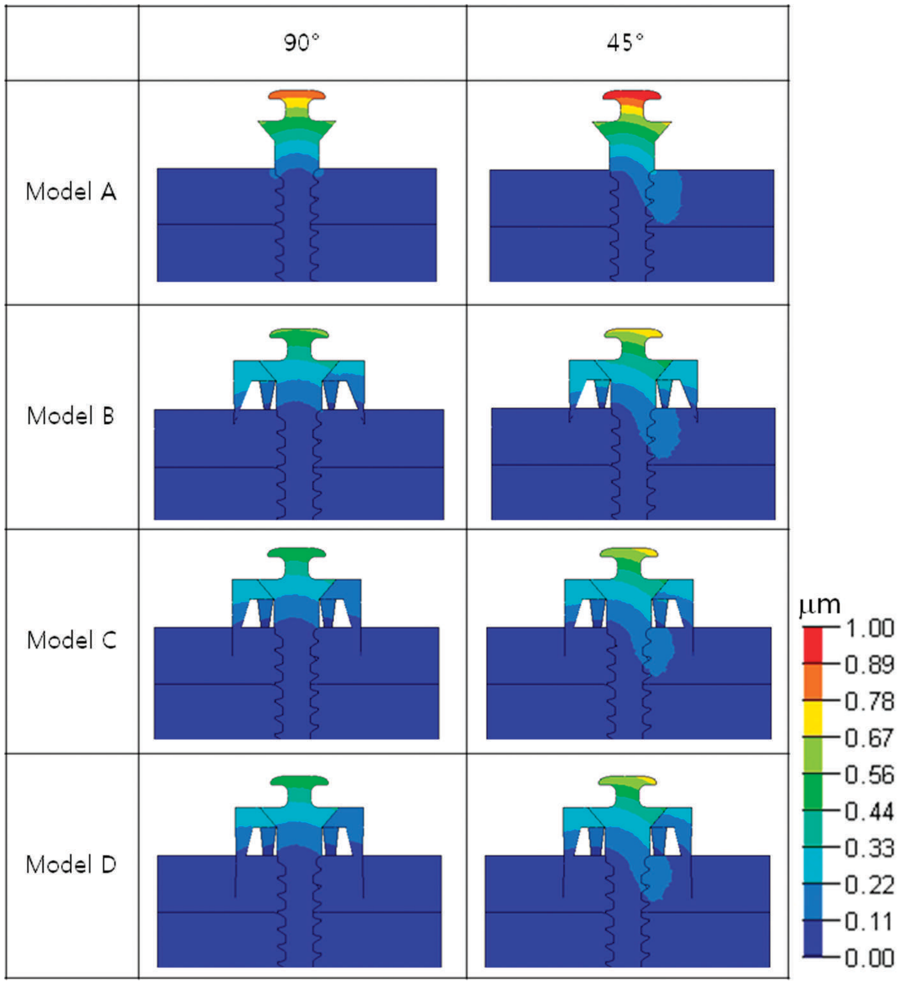

Figure 7. Displacement distribution of mini-implant.

without the washer (model A) and models with the washer (models B, C, and D); this difference is shown in the maximum tensile stress values and the stress distribution plot. In model A, the red area was distributed on the superior margin of the cortical bone, adjacent to the mini-implant and on the side opposite to the force direction. The maximum tensile stress value of model A (7.81 MPa) was significantly higher than the values of the models with the washer (model B, 5.34 MPa; model C, 5.27 MPa; model D, 4.56 MPa). In models B, C, and D, the red area corresponded to the spike area along the superior margin. However, the area of high-level stress (the red area) was obviously smaller than that of model A. As the spike length increased, the maximum tensile stress values slightly decreased, but almost no changes were observed in the plot pattern. Generally, the maximum tensile stress value was higher when the force was applied in the 45° direction. However, changes in stress values and in stress distributions exhibited similar patterns in the 90° condition (Figure 5).

Minimum Principal Stress

Minimum principal stress was used to analyze the compression stress applied to the bone elements. In the 90° condition, a remarkable difference was observed between the model without the washer and the models with the washer, in terms of both the maximum compression stress values and the stress distribution plot. In model A, the blue area (exceeding 2 MPa) was distributed on the superior margin of the cortical bone, ipsilateral to the force direction. Compared with the models with the washer, model A exhibited the lowest maximum compression stress value (6.08 MPa). In models B, C, and D, in addition to the superior margin of the cortical bone, the blue area was concentrated on the spike areas, and the maximum compression stress values were 8.27 MPa, 7.68 MPa, and 7.28 MPa, respectively. Unlike tensile stress, the maximum compression stress increased when the washer was combined with the mini-implant. However, compared with model A, the total area

Table 2. Maximum and Minimum Principal Stress Values on the Bone Element[a]

Models	Maximum Stresses, MPa 90°	Maximum Stresses, MPa 45°	Minimum Stresses, MPa 90°	Minimum Stresses, MPa 45°
A	7.81	9.75	−6.08	−5.70
B	5.34	6.70	−8.17	−7.94
C	5.27	6.35	−7.68	−7.34
D	4.56	6.28	−7.28	−7.02

[a] Tensile stress was analyzed in positive values and compression stress in negative values.

encoded in blue was reduced. As the spike length increased, almost no change was seen in the plot pattern, but absolute stress values slightly decreased. The maximum compression stress values were higher in the 45° condition than in the 90° condition, but changes in stress distribution were similar between the two force direction models (Figure 6).

Displacement

Greater maximum displacement was observed in the 45° condition compared to the 90° condition. The displacement value observed in model A was remarkably higher than those values observed in models B, C, and D, but no notable difference in displacement values was found among models B, C, and D. In conditions with the washer, a significantly decreased displacement of the head was noted from the image, and a clear difference in the displacement plot patterns was observed between the model without the washer and models with the washer. A high-level area, shown in red and orange, was observed on the head of the mini-implant in model A but not in model B, C, or D (Figure 7).

DISCUSSION

In this study, instead of increasing the interface of the mini-implant, a new structure called a washer was introduced to modify the force-moment system. The height of the washer structure led to changes in the length of the moment arm and the center of resistance of the mini-implant systems. As a result, the moment of force dropped. Based on this result, the washer has advantages related to the stress distribution on the surrounding bone and the initial displacement of the mini-implant. In addition, the increased interface resulting from the application of the washer appears to be unrelated to these positive effects.

Previous attempts to improve mini-implant stability focused primarily on modifying designs to increase the interface. These studies were based on the hypothesis of Frost,[16] which suggested to increase the interface of the implant in order to minimize the load applied on the supporting bone, and thus the load applied to the bone is kept below the bone's physiological limit. Lim et al.[9] performed FEA to determine the effect of the diameter, and they reported a decrease in the maximum stress on the bone when the diameter increased from 1.2 mm to 2.0 mm. Motoyoshi et al.[12] found that the maximum stress on the bone can be decreased by decreasing the pitch. Increasing the height of the thread was also reported by Yu and Kyung[11] to be advantageous in stress distribution. Improved stress distribution resulting from increasing the interface is obviously helpful in decreasing bone fatigue and improving the stability of the mini-implant.

Table 3. Maximum Displacement Value of Mini-Implant Element

Models	Maximum Displacement, μm 90°	Maximum Displacement, μm 45°
A	0.87	1.05
B	0.59	0.77
C	0.55	0.74
D	0.54	0.72

However, there are also disadvantages associated with increasing the interface. Increased mini-implant diameters can cause root damage.[17] If the height of the thread is increased while the diameter is unchanged, fracture resistance decreases as a result of the decreased screw core.[11] The most serious negative effect related to an increased interface is the increased torque required at insertion, and a few studies[4,10,18] have reported that high torque can have negative effects on the secondary stability of the mini-implant.

In numerous previous studies, insertion torque was used as a criterion for initial stability. However, when the insertion torque is increased as a result of the increased interface, the resulting strain in the cortical bone increases the risk of complications such as bone crack, bone necrosis, and unfavorable secondary stability.[19]

In this study, initial displacement was used as an indicator for initial stability,[12] and stress distribution was analyzed to evaluate the effects on the secondary stability.[16] Initial stability is thought to be an important factor for success. Between the 90° and 45° force direction conditions, differences were found in the maximum displacement values of the mini-implants, but the change patterns were similar. The area indicating displacement over 0.78 μm (red- and orange-colored areas) was only observed in the mini-implant head of model A. By applying the washer, the displacement of the mini-implant decreased remarkably. The washer did exhibit displacement, but it was trivial. For models B, C, and D, the displacement distribution plots were very similar. The displacement of the mini-implant decreased when utilizing the washer, but the spike length of the washer had almost no effect on the displacement of the mini-implant.

These results indicate that the washer could be effective in raising the initial stability. The positive effect of the washer on the stability of the mini-implants can be explained by the alteration in the force system rather than by the increased interface resulting from increasing the length of the spike. The differences in the displacement values between model A and models B, C, and D were obvious. However, among models B, C, and D, no remarkable differences in displacement were observed according to the different lengths of the spike. The actual increase in interface between model A and model D was trivial. Therefore, the effect of the washer is attributable primarily to the shortened moment arm.

Through the stress distribution analysis, a remarkably decreased maximum tensile strength value was observed when the washer was combined with the mini-implant. On the contrary, the maximum compression stress values increased in models with the washer because the compression stress was concentrated in the sharp ends of the spikes. However, because of the washer, the area indicating stress exceeding 2 MPa (blue-colored area) was much smaller around the cervical area of the mini-implant. This result indicates that the application of the washer could result in decreased maximum stress on the bone adjacent to the mini-implant, and this decreased maximum stress is postulated to reduce the possibility of bone fatigue failure and subsequent bone resorption.[16] Consequently, the washer could have positive effects on the secondary stability of the mini-implant. As mentioned above, this result seems to be attributable primarily to the change in force system rather than to the increased interface.

In this study, a traction force was applied in two different directions to evaluate the mini-implant's stability in the midpalatal and buccal areas. The stress value and the displacement value were greater in the 45° force direction than in the 90° force direction. However, the changes in the distribution pattern were similar between the two directions. This indicates that the washer could be effective in both the midpalatal and buccal areas.

The advantageous effect of the washer was verified in this study, but further studies are required before the washer can be applied in clinical practice. First, the soft tissue must be taken into consideration in further studies because the characteristics and thicknesses of soft tissue are different in various positions. In this study, 1 mm of relief was left for soft tissue because when excessive pressure is applied to soft tissue, necrosis of that tissue may result. In addition, further study is necessary to test the change in insertion torque due to the use of the washer because the spike of the washer may have an effect on the insertion torque of the mini-implant.

CONCLUSION

- The application of the washer could result in decreased maximum stress on the surrounding bone and decreased displacement of the mini-implant.

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