Original Article

Evaluation of miniscrew stability using an automatic embedding auxiliary skeletal anchorage device

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ABSTRACT

Objective: To clarify the in vivo effect of an automatic embedding device on miniscrew stability.

Materials and Methods: 42 miniscrews were implanted into rabbit femurs. The miniscrews with the novel auxiliary device formed the auxiliary group (n = 11 at 4 weeks; n = 11 at 8 weeks) and the miniscrews without the auxiliary device formed the nonauxiliary control group (n = 9 at 4 weeks; n = 11 at 8 weeks). Cortical bone thickness, distance from the cortical bone surface to the miniscrew head, and implantation depth of the spike were measured using micro-computed tomography. The mechanical retention force was evaluated by measuring the displacement of the miniscrew head after it was loaded perpendicular to its long axis. In the lateral displacement test, effects of the auxiliary (with vs without auxiliary), and time (4 vs 8 weeks) were assessed using the Brunner–Langer nonparametric analysis of longitudinal data in factorial experiments.

Results: The mean implantation depth of the spike in the auxiliary group at 4 and 8 weeks was 0.28 mm (median: 0.33; SD: 0.12) and 0.37 mm (median: 0.33; SD: 0.19), respectively. The retention force was approximately 2.0 to 2.8 and 1.6 to 1.8 times greater in the auxiliary group than in the nonauxiliary group at 4 and 8 weeks, respectively.

Conclusions: The auxiliary device improved the mechanical retention force without the need to increase miniscrew length or diameter. This may enable the safe use of miniscrews in difficult areas. (*Angle Orthod.* 2019;89:47–53.)

KEY WORDS: Skeletal anchorage; Animal model; Miniscrew

INTRODUCTION

Orthodontic miniscrews are useful skeletal anchorage devices that have changed the conventional concept of orthodontic treatment. Miniscrews have numerous advantages over other skeletal anchorage devices, such as easier insertion and lower surgical invasiveness, postoperative discomfort, and cost.[1] These advantages of miniscrews have led to their increased clinical use over the past decade. However, the failure rate of miniscrew implantation still remains approximately 13.5% to 18.9%.[1–3] Moreover, the restricted availability of miniscrew implantation sites has not yet been resolved. For example, miniscrews used in the buccal region must be implanted in the alveolar bone of the radicular space to avoid root injury.[4]

The main factor affecting miniscrew stability is the mechanical retention force at the interface between the miniscrew and the cortical bone after miniscrew implantation.[5,6] Another important factor is the proximity of the miniscrew to the root. Several clinical studies and animal experiments have shown that root proximity

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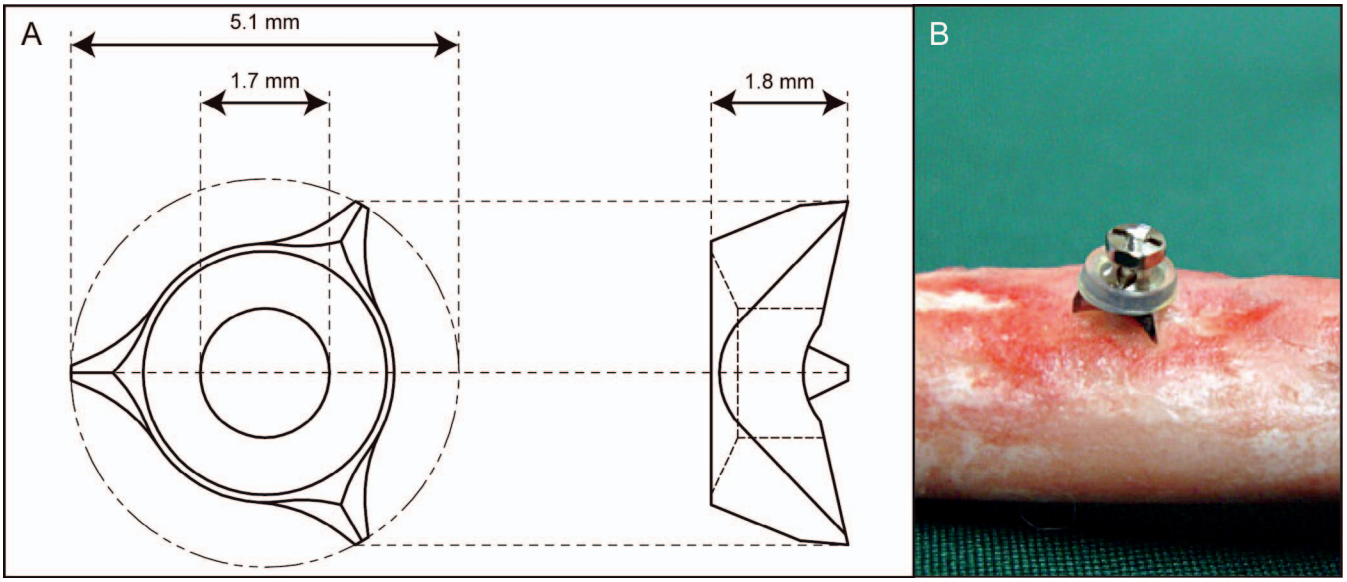

Figure 1. (A) Design of the auxiliary skeletal anchorage device used in this study. (B) Miniscrew implanted into the bone with the silicone ring and the auxiliary device.

is a significant risk factor of miniscrew failure.[7,8] These crucial factors associated with miniscrew failure, however, are contradictory. Increasing the miniscrew diameter and length enhances the stability, but it also increases the risk of root proximity.[9] Therefore, clinicians should carefully assess the radicular space and select appropriately sized miniscrews for implantation in the buccal region.

To date, several new designs of skeletal anchorage devices have been introduced to increase miniscrew stability, including the washer,[10,11] mini-implant ring,[12] and spiky miniplate.[13] However, the development of a clinically reliable skeletal anchorage device is still pending. Recently, an auxiliary device comprising a washer with spiked portions and silicone ring was reported.[14] The washer receives the compression stress of the silicone ring from the screw neck, and the spiked portion is consequently pressed on the cortical bone after implantation. The study showed that the retention force of the miniscrew with the auxiliary unit was greater than that of the miniscrew alone when implanted into artificial bone. However, it is unclear whether the auxiliary device can effectively improve the mechanical retention force of the miniscrew in vivo and how the auxiliary device may influence the biological response.

The purpose of the present study was to clarify the effect of the auxiliary device on miniscrew stability *in vivo* using an animal model. The mechanical retention force and biological response in the area surrounding the miniscrew was examined using micro-computed tomography (micro-CT) over time to compare the differences between miniscrews implanted with and without the auxiliary skeletal anchorage device.

MATERIALS AND METHODS

Conventional miniscrews measuring 1.6 mm in diameter and 6.0 mm in length (Dual-Top; Jeil Medical, Seoul, Korea), auxiliary skeletal anchorage devices measuring 5.1 mm in diameter and 1.8 mm in height (raw material, Ti6Al4V; ASTM F136-96, PCT International Publication No. WO 2014/ 088116 A1) (Figure 1A), and silicone rings (thickness, 1.0 mm; Durometer Shore A, 18; tensile strength, 4.14 MPa [600 psi]; tearing strength, 45; tensile elongation, 700%; elastic modulus, 0.82 MPa; Bitec Global Group, Tokyo, Japan) were used. The auxiliary device consisted of

Table 1. Comparison of Cortical Bone Thickness at the Implantation Site Between the Auxiliary and Nonauxiliary Groups[a,b]

Time After Implantation	Thickness (mm)				
	Auxiliary Group		Nonauxiliary Group		
	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)	*P* Value
4 weeks	1.33 ± 0.16	1.31 (1.20–1.54)	1.41 ± 0.17	1.42 (1.29–1.53)	.478
8 weeks	1.41 ± 0.23	1.37 (1.26–1.55)	1.44 ± 0.14	1.42 (1.32–1.47)	.295

[a] SD indicates standard deviation; IQR, interquartile range.
[b] Statistical method: Mann-Whitney *U*-test.

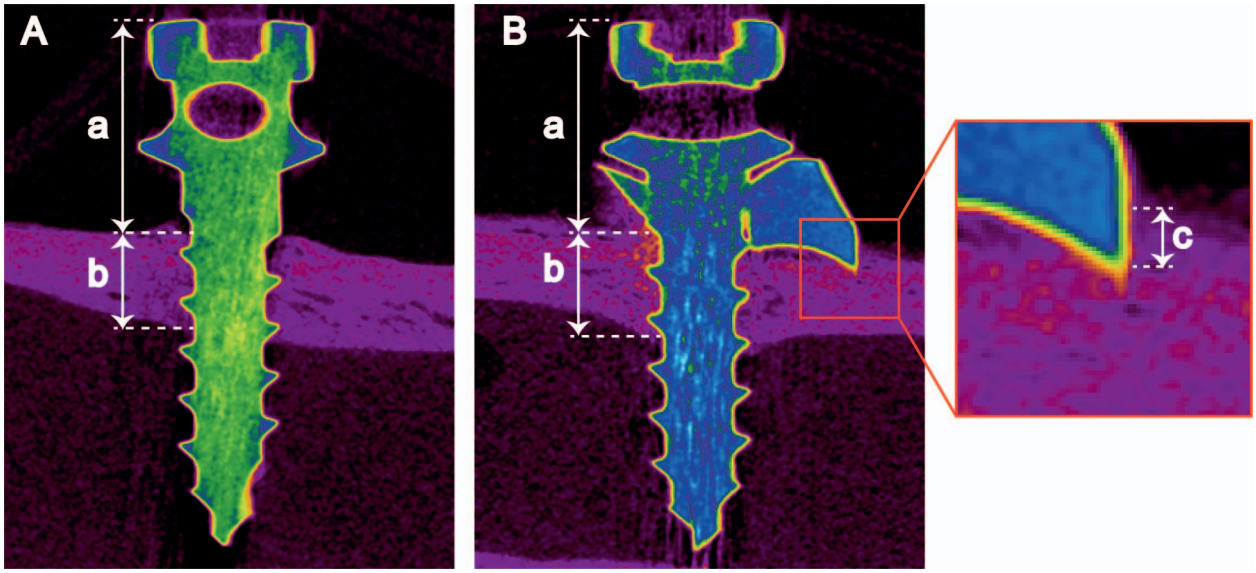

Figure 2. (A) Miniscrew without the auxiliary skeletal anchorage device. (B) Miniscrew with the auxiliary skeletal anchorage device. (a) Distance from the cortical bone surface to the top of the miniscrew. (b) Cortical bone thickness. (c) Embedded depth of the spike.

the washer and the spiked portion, which had three spikes. Implantation was performed. First, the miniscrew was implanted with the auxiliary device after placing the silicone ring between them to ensure adequate compression (Figure 1B). The washer portion of the auxiliary device received the compression stress of the silicone from the screw neck and, consequently, the spiked portion was pressed into the cortical bone. After embedding the spiked portion of the auxiliary device into the cortical bone, the silicone ring was removed and the miniscrew was further tightened.[14]

Eleven adult female Japanese white rabbits (age, 14 weeks; weight, 2.5–3.0 kg) were used as experimental models in this study. The animal experimental protocol was approved by the institutional experimentation committee of Kagoshima University (No. 14031).

All experimental animals were injected intramuscularly with ketamine (35 mg/kg) and xylazine (0.2 mg/kg) to induce general anesthesia and with 2% lidocaine containing 1:80,000 epinephrine to induce local anesthesia. The muscle tissue around the femur was bluntly separated, and the femur was exposed. The miniscrews were implanted into the middle of the femurs with a driver, such that the distance from the cortical bone surface to the miniscrew head was approximately 3.5 mm. After confirming the miniscrews were immobile, the incised skin was sutured with 3-0 nylon. Four miniscrews were implanted per animal. First, one miniscrew alone and one miniscrew with auxiliary were implanted into every left leg. Miniscrews were then implanted into every right leg using the same technique at 4 weeks; however, two miniscrews without auxiliary devices were removed immediately during the surgical procedure due to small bone cracks occurring around the miniscrews. All animals were subsequently euthanized at 8 weeks. The silicone rings were then removed and the miniscrews were further tightened. The bone blocks containing the miniscrews were excised and frozen at –20°C.[15,16] Previous reports demonstrated that the main remodeling of the surrounding bone after implant insertion occurred between 2 and 4 weeks,[17,18] and bone-implant contact changed little after more than 6 or 8 weeks.[19,20] In the present study, observation periods of 4 and 8 weeks were used.

In total, 42 miniscrews were implanted. The biological response of the bone around the miniscrews and the mechanical retention force in the group that

Table 2. Comparison of the Distance From the Cortical Bone Surface to the Top of of the Miniscrew Between the Auxiliary and Nonauxiliary Groups [a,b]

Time After Implantation	Distance (mm)				
	Auxiliary Group		Nonauxiliary Group		
	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)	*P* Value
4 weeks	3.52 ± 0.15	3.51 (3.44–3.64)	3.57 ± 0.24	3.54 (3.42–3.79)	.710
8 weeks	3.53 ± 0.16	3.52 (3.37–3.68)	3.40 ± 0.22	3.44 (3.25–3.55)	.171

[a] SD indicates standard deviation; IQR, interquartile range.
[b] Statistical method: Mann-Whitney *U*-test.

Table 3. Implantation Depth of the Spike at 4 and 8 Weeks in the Auxiliary Group

	4 Weeks		8 Weeks	
	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)
Depth (mm)	0.28 ± 0.12	0.33 (0.15–0.39)	0.37 ± 0.19	0.33 (0.23–0.51)

[a] SD indicates standard deviation; IQR, interquartile range.

received the auxiliary device (auxiliary group; n = 11 at 4 weeks, and n = 11 at 8 weeks) and in the group that did not (nonauxiliary group; n = 9 at 4 weeks, and n = 11 at 8 weeks) were evaluated. The specimens were scanned using a micro-CT scanner (Skyscan 1272; Bruker Corporation, Billerica, MA) at 100 kV and 100 mA and the exposure time was 911 ms. The image pixel size was 16 μm.[21] Using DataViewer software (Version 1.5.2; Bruker Corporation), cortical bone thickness and the distance from the cortical bone surface to the miniscrew head were measured in the cross-sectional and longitudinal planes which ran parallel to the long axis of the miniscrew at four points (anterior, posterior, proximal, and distal) on the three-dimensional images. The average thickness and distance of the four points were then calculated. The implantation depth of the spike was measured from three spike apices to the bone surface parallel to the long axis of the miniscrew using the same software and the average depth of the three points was calculated (Figure 2A, 2B).

The mechanical retention force was evaluated by measuring the displacement of the miniscrew head.[12,22] The specimens were embedded into the plaster cube such that the long axis of the miniscrew was perpendicular to the bottom of the cube and the long axis of the femur was perpendicular to the side of the cube. Twelve hours after embedding the specimens into the cubes (Figure 3A), the displacement of the miniscrew head was measured after bidirectional loading using a compression test machine (TGE-5kN; Minebea, Nagano, Japan) set at a load of 5.0 kN and a compression velocity of 0.5 mm/min (Figure 3B). The two opposite loading directions were parallel to the long axis of the femur (Figure 3C). The load force was delivered until each miniscrew moved 0.01, 0.02, and 0.03 mm from its initial position, as calculated using a software program (SR-06-001 version 3.400; Minebea). The average force applied in the two directions was then calculated.

Statistical Analysis

IBM SPSS Statistics software, Version 23 (IBM Corp., Armonk, NY) was used for micro-computed tomography data analysis, which included values for mean, standard deviation (SD), median, and the range from the lower quartile (25th percentile) to the upper quartile (75th percentile). The cortical bone thickness and distance from the cortical bone surface to the miniscrew were compared between the auxiliary and nonauxiliary groups at 4 and 8 weeks after implantation using the Mann-Whitney *U*-test. In the lateral displacement test, effects of the auxiliary (with vs without auxiliary), and time (4 vs 8 weeks) were assessed using the Brunner–Langer nonparametric analysis of longitudinal data in factorial experiments with R software, version 3.4.4 (R foundation for Statistical Computing, Vienna, Austria) using the package nparLD.[23,24] The relative treatment effect (RTE) was interpreted as follows: values below and above 0.5 indicated a decrease and increase in the outcome variable, respectively. Values with $P < .05$ were considered statistically significant.

RESULTS

Results measured using micro-computed tomography images are presented in Tables 1–3. The median cortical bone thickness of the specimens in the auxiliary and nonauxiliary groups at 4 weeks was 1.33 mm (median: 1.31; SD: 0.16) and 1.41 mm (median: 1.42; SD: 0.17), respectively, and the difference was not statistically significant ($P > .05$). The mean cortical bone thickness of the specimens in the auxiliary and nonauxiliary groups at 8 weeks was 1.41 mm (median: 1.37; SD: 0.23) and 1.44 mm (median: 1.42; SD: 0.14), respectively, and the difference was not statistically significant ($P > .05$). The mean implantation depth of the spike in the auxiliary group at 4 weeks and 8 weeks was 0.28 mm (median: 0.33; SD: 0.12) and 0.37 mm (median: 0.33; SD: 0.19), respectively.

In the lateral displacement test, it was revealed, using the Brunner-Langer nonparametric analysis, that auxiliary effects at miniscrew displacements of 0.01, 0.02, and 0.03 mm were significant (with vs without auxiliary; 0.01 mm, 0.02 mm and 0.03 mm, $P < .001$) but time effects were not significant (4 vs 8 weeks; 0.01 mm, $P = .966$; 0.02 mm, $P = .283$; and 0.03 mm, $P = .0948$) (Table 4, Figure 4). The retention force at 4 and 8 weeks was greater in the auxiliary group than in the nonauxiliary group at miniscrew displacements of 0.01, 0.02, and 0.03 mm.

Table 4. Comparison of Mechanical Retention Forces Between the Auxiliary and Nonauxiliary Groups at 4 and 8 Weeks After Implantation

Displacement (mm)	Compression Force (N) 4 Weeks			
	Auxiliary Group		Nonauxiliary Group	
	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)
0.01	3.10 ± 1.33	2.97 (1.77–4.38)	1.43 ± 0.43	1.48 (1.07–1.67)
0.02	6.61 ± 1.83	6.79 (4.83–8.08)	2.55 ± 0.99	2.40 (1.97–3.09)
0.03	10.14 ± 2.28	10.82 (8.21–11.87)	4.23 ± 1.54	4.03 (3.11–4.95)
Displacement (mm)	Compression Force (N) 8 Weeks			
	Auxiliary Group		Nonauxiliary Group	
	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)
0.01	3.03 ± 1.03	2.69 (2.16–3.84)	1.52 ± 0.47	1.61 (1.16–2.02)
0.02	6.56 ± 1.25	5.97 (5.65–7.52)	3.11 ± 1.01	3.33 (2.59–3.82)
0.03	10.49 ± 1.7	9.35 (8.43–12.37)	5.33 ± 1.7	5.71 (4.38–6.72)

[a] SD indicates standard deviation; IQR, interquartile range.

DISCUSSION

In the present study, to evaluate the mechanical retention force of the miniscrews with and without the auxiliary device, the lateral displacement test was used.[12,22] Several studies have evaluated the stability of the implant by measuring insertion torque, removal torque, and pull-out strength.[5,25] However, measuring the insertion and removal torques cannot confirm the movement of the miniscrew during loading. Moreover, the pull-out test is performed with an axial force, which is rarely experienced in the clinical orthodontic setting. Although the lateral displacement test cannot measure the resistance to the pull-out force, it can measure the relationship between the force delivered perpendicularly and the displacement of the miniscrew. This test is also consistent with how the force is clinically applied to a miniscrew, and it is more suitable than the other tests for evaluating implant stability.

This study showed that the retention force was approximately 2.0 to 2.8 and 1.6 to 1.8 times greater in the auxiliary group than in the nonauxiliary group at 4 and 8 weeks, respectively. It was considered that the spikes of the auxiliary device contributed to resisting the load delivered to the screw head, because the spikes were embedded a mean of 0.28 mm (median: 0.33) and 0.37 mm (median: 0.33) into the cortical bone at 4 and 8 weeks, respectively. Addition of cortical bone may also have occurred around the spike apices. Numerous studies have reported that initial bone formation around titanium implants occurs

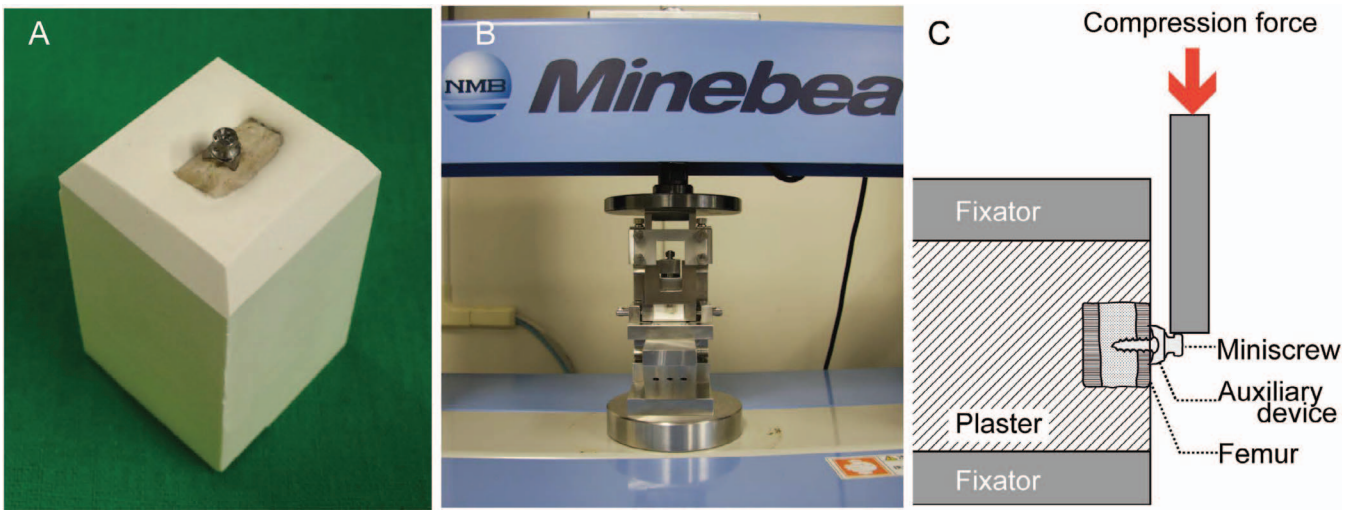

Figure 3. (A) The specimen embedded in a plaster block. (B) The plaster block containing the embedded specimen was fixed on a compression test machine for the lateral displacement test. (C) Schema of the lateral loading test. Compression force was applied perpendicular to the miniscrew head.

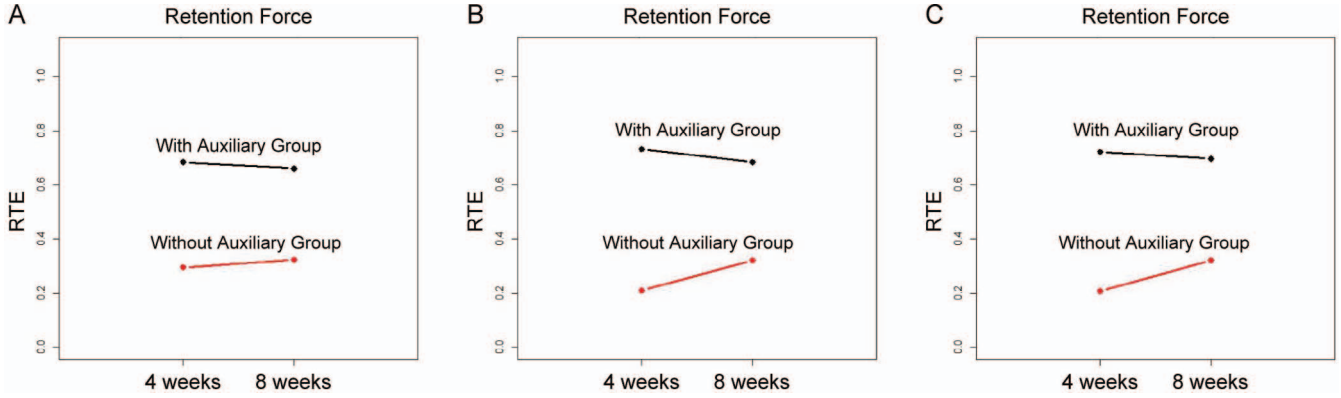

Figure 4. Estimates of the relative treatment effect (RTE) for the mechanical retention force of miniscrews with and without the auxiliary at 4 and 8 weeks after implantation at miniscrew displacements of: (A) 0.01 mm, (B) 0.02 mm, and (C) 0.03 mm.

vertically along the implant surface.[26,27] Additionally, previous investigators observed more extracortical bone formation around the abutment and above the implant neck of the rabbit tibia in the loading group.[28] The study might suggest that the bone formation that embedded the spike apices resulted from the force applied by the apices to the cortical bone surface. Another previous study performed a finite element analysis to investigate the biomechanical effects of a "washer" (which was similar to that used in the current auxiliary device) designed for improving mini-implant stability.[10] The authors of that study concluded that the application of the washer could result in decreased maximum stress on the surrounding bone and decreased displacement of the mini-implant. The same phenomenon is also thought to have occurred in the current experiments.

The auxiliary device has two advantages. First, it can improve the stability due to the mechanical connection between the miniscrew and the surrounding bone after implantation. Second, it can reduce the risk of root proximity and contact. Several previous studies have shown that the stability and implantation success rate can be improved by increasing the diameter and length of the miniscrew, which increases the interface between the miniscrew and the bone.[29–31] Although increasing the diameter and length of the miniscrew is beneficial for stability, it simultaneously increases the risk of root proximity and damage, which can significantly increase the risk of miniscrew failure.[7,8] The auxiliary device may enable the use of a shorter and narrower miniscrew because an increase in the contact area with the cortical bone may enhance the mechanical retention force.

Another critical risk factor of dental implant failure is peri-implantitis, which causes the resorption of bone in contact with a dental implant and the loss of osseointegration. Severe inflammation of the tissue surrounding the miniscrew has been suggested to cause bone resorption and miniscrew failure.[2,32] The complexity of the auxiliary device may exacerbate the surrounding hygiene and cause bacterial infection and inflammation when applied in the oral cavity. Additionally, histological changes in the bone tissue could not be evaluated in this study. Therefore, further studies using a dog model are needed to confirm the safety and stability of the novel auxiliary device, including evaluation of histological responses and changes in the soft and hard tissues, in an environment similar to the human oral cavity.

CONCLUSIONS

- The automatic embedding auxiliary skeletal anchorage device increased miniscrew stability by a factor of 1.6 to 2.8 on median compared with the miniscrew alone in vivo.
- This newly developed auxiliary device may enable the use of miniscrews that are shorter in length and narrower in diameter, making them safer to use in difficult areas.

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