

Original Article

Microdamage generation by tapered and cylindrical mini-screw implants after pilot drilling

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ABSTRACT

Objective: To investigate the relationship between mini-screw implant (MSI) diameter (1.6 vs 2.0 mm) and shape (tapered vs cylindrical) and the amount of microdamage generated during insertion.

Materials and Methods: Thirty-six cylindrical and 36 tapered MSIs, 6 mm long, were used in this study. Half of each shape was 1.6 mm in diameter, while the other half was 2.0 mm. After pilot drilling, four and five MSIs were inserted, respectively, into fresh cadaveric maxillae and mandibles of dogs. Bone blocks containing the MSIs were sectioned and ground parallel to the MSI axis. Epifluorescent microscopy was used to measure overall cortical thickness, crack length, and crack number adjacent to the MSI. Crack density and total microdamage burden per surface length were calculated. Three-way analysis of variance (ANOVA) was used to test the effects of jaw, and MSI shape and diameter. Pairwise comparisons were made to control the overall significance level at 5%.

Results: The larger (2.0 vs 1.6 mm) cylindrical MSIs increased the numbers, lengths, and densities of microcracks, and the total microdamage burden. The same diameter cylindrical and tapered MSIs generated a similar number of cracks and crack lengths. More total microdamage burden was created by the 2.0-mm cylindrical than the 2.0-mm tapered MSIs. Although higher crack densities were produced by the insertion of 1.6-mm tapered MSIs, there was no difference in total microdamage burden induced by 1.6-mm tapered and 1.6-mm cylindrical MSIs.

Conclusions: Pilot drilling is effective in reducing microdamage during insertion of tapered MSIs. To prevent excessive microdamage, large diameter and cylindrical MSIs should be avoided. (*Angle Orthod.* 2015;85:859–867.)

KEY WORDS: Mini-screw implants; Microdamage; Tapered; Cylindrical

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INTRODUCTION

Mini-screw implants (MSIs) have been widely used as orthodontic skeletal anchorage.^{1,2} Because of their relatively small diameters (1.2 to 2 mm), they can be placed in various sites of the jaws to accomplish challenging treatment.^{3–5} With immediate loading and requiring minimal patient compliance, MSIs facilitate efficient and predictable treatment.^{6,7} However, MSI success rates (83.8%–91.6%) have not been completely satisfactory.^{8–10}

At placement, success is indicated by “primary” stability.¹¹ While some recommend 5–10 Ncm insertion torques,¹² in general, higher insertion torque would

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Table 1. Experimental Design: Four Groups of Mini-screw Implants (18 Per Group) Were Placed in Four Dogs^a

	Dog 1		Dog 2		Dog 3		Dog 4	
Maxilla	1.6 T (n = 4)	2.0 T (n = 4)	1.6 C (n = 4)	2.0 C (n = 4)	1.6 T (n = 4)	1.6 C (n = 4)	2.0 T (n = 4)	2.0 C (n = 4)
Mandible	1.6 T (n = 5)	2.0 T (n = 5)	1.6 C (n = 5)	2.0 C (n = 5)	1.6 T (n = 5)	1.6 C (n = 5)	2.0 T (n = 5)	2.0 C (n = 5)

^a 1.6 indicates 1.6 mm; 2.0, 2.0 mm; T, tapered; and C, cylindrical.

produce greater primary stability.^{13,14} But, excessive insertion torque produces potential failure due to bone necrosis,¹⁵ microdamage,^{16,17} or MSI fracture during insertion.¹⁸

To avoid excessive insertion torque, one approach is to change the shape of the MSI. For example, some studies demonstrate that tapered MSIs generate higher insertion torque with higher primary stability than cylindrical MSIs,^{3,7,19–21} but they can produce excessive insertion torques, potentially damaging the bone.^{13,17,22–24} The latter findings correspond to finite element analyses, which suggest that tapered MSIs induce high stresses in the cortical bone²⁵ around the implant neck.²⁶

Another way to reduce insertion torque is with pilot holes. A study showed that, without pilot drilling, tapered MSIs produce a greater number of cracks and increased crack length than cylindrical MSIs.¹⁷ In another study, pilot drilling lessened microdamage during insertion of 1.6-mm cylindrical MSIs.²⁷ Another study using 1.0-mm diameter pilot drilling found that it significantly reduced microdamage even with the insertion of larger diameter (1.4-, 1.6-, and 2.0-mm) cylindrical MSIs.²⁸ While microdamage stimulates bone remodeling and induces a periodontal ligament (PDL)-like zone around conventional dental implants,^{29–32} accumulated microdamage can weaken bone^{33–35} and potentially jeopardize MSI stability.¹⁷

To understand how pilot drilling and MSI taper affect primary stability, researchers inserted tapered and cylindrical MSIs perpendicular to artificial bone blocks and found similar maximum insertion torques with the same pilot drilling.³⁶ In a similar design, but with MSIs placed at an angle to mimic a clinical scenario, tapered MSIs created higher insertion torque than cylindrical MSIs. The conclusions of these studies are limited due to the use of artificial bone. To date, there is no literature about the effects of pilot drilling on the production of microdamage by tapered MSIs with different diameters. Thus, the purpose of this study is to investigate microdamage production in the maxilla and mandible of dogs by tapered and cylindrical MSIs with varying diameters.

MATERIALS AND METHODS

Seventy-two titanium alloy (6Al4V) MSIs, with 6-mm threads, were used in this study. Half of them was tapered (AbsoAnchor SH15-16, Dentos, Daegu,

Korea), while the others were cylindrical (Dual-Top Temporary Anchorage Device, Rocky Mountain Orthodontics, Denver, CO, USA). Both sets were further divided into 1.6- and 2.0-mm diameter groups, yielding four groups (n = 18) of MSIs (tapered, 1.6; tapered, 2.0; cylindrical, 1.6; and cylindrical, 2.0). They were inserted into the maxillary and mandibular quadrants of four cadaveric mongrel adult dogs (20–25 kg and 1–1.5 years old) using an unbalanced random block design (Table 1). The dogs had been euthanized for another study that was approved by The Institutional Animal Care and Use Committee. Within 4 hours of being humanely killed, mucosa and periosteum were reflected, and pilot holes were drilled perpendicular to the bone surface with a 1.0-mm diameter (6 mm long) surgical drill (Dentaurum, Newton, Pa) with a contra-angle handpiece (Aseptico, Woodinville, Wash) and copious saline irrigation. The MSIs were inserted manually by one operator with the manufacturers' screwdrivers. The maxillary and mandibular quadrants received four and five MSIs, respectively (Figure 1).

Each MSI with its surrounding (1.5 cm × 1.5 cm) bone block was dissected, coded, immediately submerged, and fixed in 70% ethyl alcohol for 7 days, stained in 1% basic fuchsin hydrochloride in a graded series of alcohols under vacuum and embedded in methyl methacrylate.²⁸ The blocks were cut and ground parallel to the MSI axis to approximately 200 microns with an Exakt grinder (Exakt Technologies Inc, Nordersted, Germany). Identification of microdamage was done under a 10× epifluorescence microscope (Leica, Buffalo Grove, Ill) with excitation wave length 546 nm using previously published criteria.²⁸ Cortical thickness, crack length, and crack number adjacent to

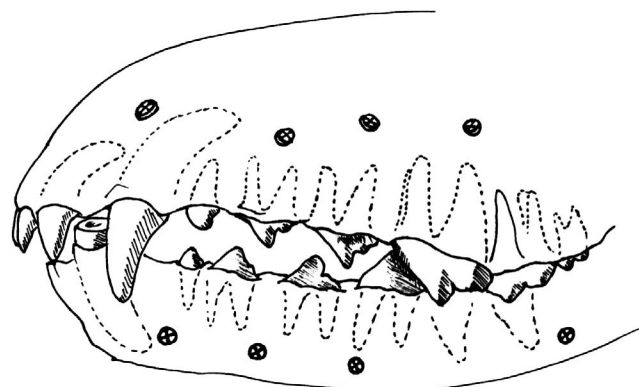


Figure 1. Illustration of placement position of mini-screw implant.

Table 2. Definition of Parameters

Parameter	Definition	Unit
Cortical thickness	Average length of cortical thickness	μm
Implant surface length	Traced surface length adjacent to the mini-screw implant under epifluorescence microscope	μm
Crack number	Number of total cracks	number
Crack length	Traced crack length adjacent to the mini-screw implant under epifluorescence microscope	μm
Crack density	Crack number/mini-screw implant surface length	number/μm
Total microdamage burden per surface length	Crack number × mean crack length/implant surface length	μm/μm

the MSI, and the MSI surface length in cortical bone were measured using Bioquant Osteo II software (Bioquant Image Analysis Corporation, Nashville, Tenn). Crack density and total microdamage burden were calculated as crack number/MSI surface length and crack number × mean crack length/implant surface length, respectively. Parameter definitions are listed in Table 2.

Three-way analysis of variance (ANOVA) was used to test the effects of diameter (1.6 and 2.0 mm), jaw (maxilla and mandible), and MSI shape (tapered and cylindrical) and their interactions with cortical bone thickness, crack length and density, and total microdamage burden. Pairwise comparisons were made to control the overall significance level at 5%.

RESULTS

Cortical thickness and microdamage parameters (implant surface length, crack number, length and density, and total microdamage burden per surface length) are listed in Table 3.

MSIs of the same shape, inserted in similar cortical bone thickness, showed similar implant surface length (Table 4). The 2.0-mm cylindrical MSIs introduced significantly greater crack numbers, lengths and densities, and total microdamage burden than the 1.6-mm cylindrical MSIs (Figures 2 and 3). No differences were found between 1.6-mm and 2.0-mm tapered MSIs. Same diameter cylindrical and tapered MSIs were inserted into similar cortical bone thickness (Table 5), and the former demonstrated significantly longer implant surfaces than the latter. More cracks, longer crack length, and higher total microdamage burden were created by the 2.0-mm cylindrical MSIs than the 2.0-mm tapered MSIs. Higher crack density was found for 1.6-mm tapered MSIs compared with 1.6-mm cylindrical MSIs, but there was no difference in total microdamage burden (Figures 3 and 4). The mandible showed significantly greater overall cortical thickness than the maxilla (Table 6), and a significantly longer implant surface. MSI insertion created similar crack length and density and total microdamage burden in the maxilla and mandible. However, the

Table 3. Cortical Thickness, Implant Surface, and Microdamage Parameters Including Number of Cracks, Crack Length, Crack Density, and Total Microdamage Burden Per Surface Length, Generated by Insertion of 1.6-mm and 2.0-mm Cylindrical and Tapered Mini-screw Implants in the Dog Maxilla and Mandible

Mini-screw Implants	Cortical Thickness, μm		Implant Surface, μm		Number of Cracks		Crack Length, μm		Crack Density (Number of Cracks/μm) × 10 ⁻³		Total Microdamage Burden Per Surface Length, μm/μm	
	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error
Maxilla												
1.6 mm												
Cylindrical	1414.35	165.03	4330.42	646.12	4.87	1.09	299.73	43.70	1.08	0.14	0.35	0.08
Tapered	1711.57	196.87	5209.18	813.32	5.43	0.69	226.68	13.32	1.29	0.30	0.29	0.07
2.0 mm												
Cylindrical	1385.96	133.89	4017.91	368.41	4.75	0.45	362.37	53.07	1.22	0.11	0.40	0.03
Tapered	1685.60	201.62	4928.34	771.24	4.14	0.77	256.46	26.63	0.98	0.23	0.25	0.05
Mandible												
1.6 mm												
Cylindrical	2368.70	153.33	6927.88	649.24	6.12	0.97	225.02	24.67	0.87	0.09	0.19	0.02
Tapered	2216.76	71.365	6395.79	392.12	6.78	0.80	309.46	26.80	1.10	0.16	0.34	0.05
2.0 mm												
Cylindrical	2221.54	108.95	6805.96	432.40	9.10	0.43	341.61	26.38	1.40	0.12	0.46	0.04
Tapered	2016.68	64.743	6136.03	167.74	6.00	0.80	229.53	21.41	0.97	0.12	0.23	0.04

Table 4. Comparison of Cortical Thickness, Implant Surface, and Microdamage Parameters Including Number of Cracks, Crack Length, Crack Density, and Total Microdamage Burden Per Surface Length Between 1.6-mm and 2.0-mm Mini-screw Implants With the Same Shape

Mini-screw Implants	Cortical Thickness, μm		Implant Surface, μm		Number of Cracks		Crack Length, μm		Crack Density (Number of Cracks/ μm) $\times 10^{-3}$		Total Microdamage Burden Per Surface Length, $\mu\text{m}/\mu\text{m}$	
	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value
Cylindrical												
1.6 mm	1956.35 (143.30)	.894	6512.22 (805.44)	.711	5.33 (0.88)	.005*	260.02 (26.88)	.004*	0.78 (0.20)	.002*	0.21 (0.07)	<.001*
2.0 mm	1936.89 (140.51)		6327.11 (800.71)		7.64 (0.86)		362.33 (25.85)		1.27 (0.20)		0.46 (0.07)	
Tapered												
1.6 mm	1831.22 (144.06)	.795	4877.98 (807.67)	.623	5.46 (0.88)	.917	262.43 (27.01)	.605	1.24 (0.20)	.895	0.30 (0.07)	.865
2.0 mm	1792.36 (143.87)		4627.11 (806.74)		5.38 (0.88)		244.39 (27.02)		1.21 (0.20)		0.31 (0.07)	

* Statistical significance ($P < .05$).

2.0-mm MSIs produced significantly greater crack numbers in the mandible than in the maxilla.

DISCUSSION

To date, no studies have compared microdamage generated by insertion of cylindrical and tapered MSIs of different diameters into pilot-drilled bone. Our results revealed that 2.0-mm cylindrical MSIs generated significantly greater crack numbers, lengths and densities, and total microdamage burden than 1.6-mm cylindrical MSIs (Table 4). This is consistent with the findings of Lee and Baek¹⁷ that larger diameter MSIs produced greater microdamage than smaller diameter MSIs. The adjacent bone is compressed as an MSI is inserted.²⁶ With the same size pilot hole and homogeneous cylindrical shape between the pilot hole and MSI, insertion of a larger diameter MSI increases the stresses in bone. Microdamage is likely caused by a combination of compressive radial stresses and circumferential tensile stresses within the bone.

In contrast, tapered 2.0-mm and 1.6-mm MSIs generated similar amounts of crack numbers, lengths and densities, and total microdamage burden (Table 4). When inserting tapered MSIs into a cylindrical pilot hole, less bone is compressed due to shorter implant surface length (or contact between the bone and MSI) because of the shape difference. Therefore, bone compression by larger sized tapered MSIs is diminished.

Cylindrical MSIs had longer surfaces in cortical bone than tapered MSIs due to the decreasing diameter of the latter toward the tip (Table 4). Only the crack density was significantly higher with tapered than cylindrical 1.6-mm MSIs, probably because the cracks were distributed along a significantly reduced implant

surface length. Notably, tapered MSIs did not generate more total microdamage burden than cylindrical MSIs. This supports our hypothesis that pilot drilling is effective in reducing microdamage during insertion of tapered MSIs. This is also consistent with Yadav et al.,²⁷ who found that pilot drilling effectively reduces microdamage compared to self-drilling. Gantous and Phillips³⁷ and Heidemann et al.³⁸ recommended that the pilot hole size be only up to 85% of the width of the inner diameter for increased stability.³⁶ In the present study, the inner diameter is 0.8–0.9 mm for the 1.6-mm tapered MSI and 0.92 mm for the 1.6-mm cylindrical MSI, or 80%–92% of the 1-mm pilot hole in width. Therefore, the likelihood of overcompression was significantly reduced. Without pilot drilling, Lee and Baek¹⁷ showed that insertion of tapered MSIs created more microdamage than cylindrical MSIs, probably because more stresses accumulated surrounding the neck of tapered MSIs.^{25,26}

Interestingly, 2.0-mm cylindrical MSIs created significantly greater number of cracks, crack length, and total microdamage burden than tapered MSIs (Table 5). The inner diameter of 2.0-mm cylindrical MSIs is 1.08 mm, while the straight (cylindrical) surgical pilot drill was 1.0 mm in diameter. However, the amount of microdamage generated from differences in diameter between the inner diameter of the MSI and pilot hole is likely negligible. When inserting 2.0-mm cylindrical MSIs in the pilot hole, the adjacent bone is constantly compressed by the thread, resulting in higher crack numbers and length and resulting total microdamage burden. The parallel threads of the cylindrical MSI engage greater cortical bone surface area than the tapered shape because of the uniform diameter of the cylindrical MSI. This

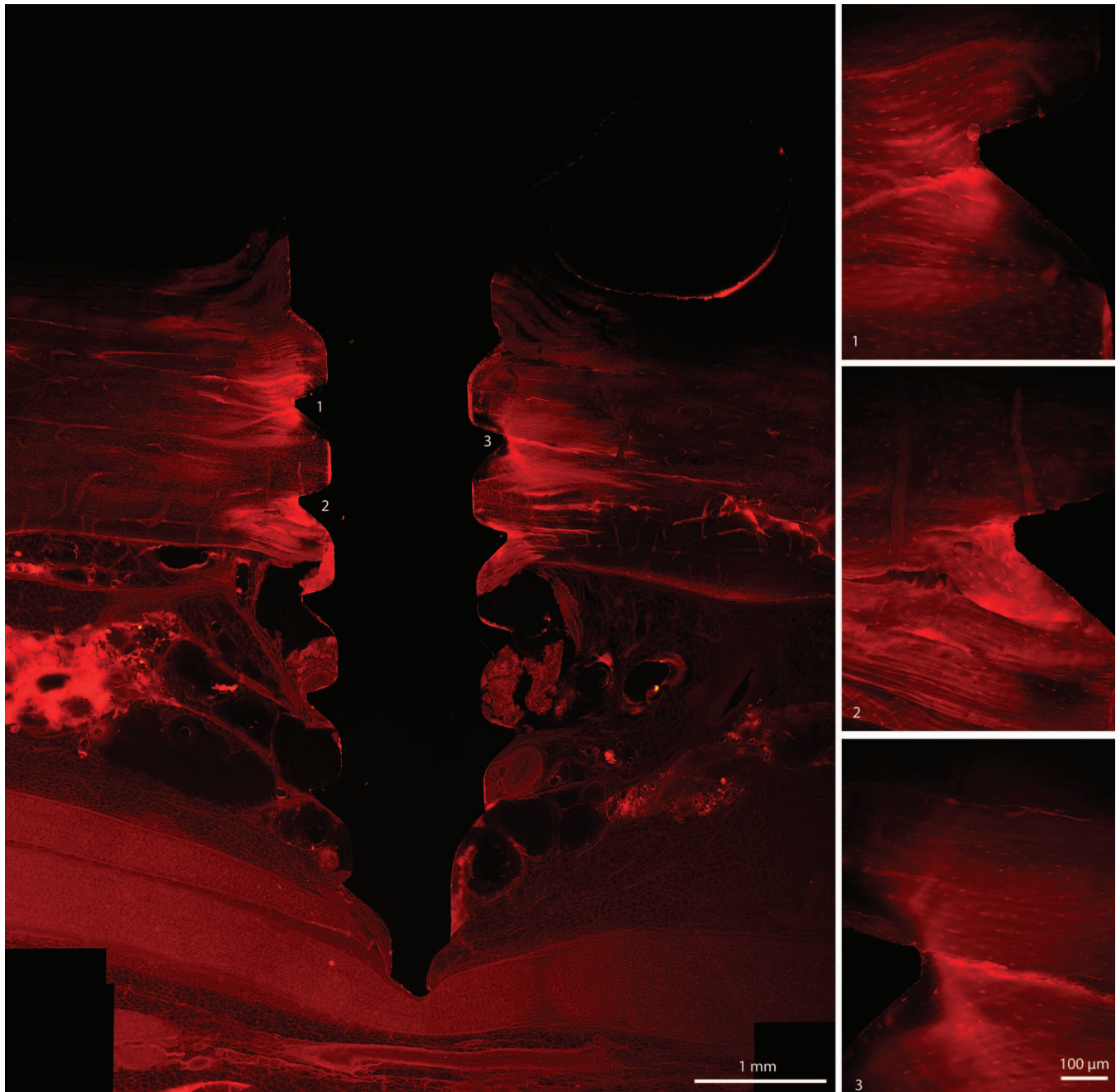


Figure 2. Cylindrical mini-screw implants, 1.6-mm diameter, with microdamage.

indicates that pilot drilling is not as effective in reducing microdamage caused by larger cylindrical MSIs as with tapered MSIs.

Despite structural differences, the cortical thickness of these dog maxillae and mandibles are comparable to adult patients.³⁹ Consistent with a previous study,²⁸ cortical bone of the mandible is thicker than that of the maxilla (Table 6). With greater cortical thickness, longer implant surfaces were shown with all mandibular MSIs. It was expected that more microdamage

would occur in the mandible because of its greater cortical thickness and higher mineralization.²⁹ Our data showed that MSI insertion in the mandible produces a larger number of cracks, but it did not induce greater crack length, crack density, or total microdamage burden. Although more cracks were created by the longer distance that the thread travels through the cortical bone, this suggests that pilot drilling can still effectively relieve the overcompression of cortical bone. This may explain why MSI

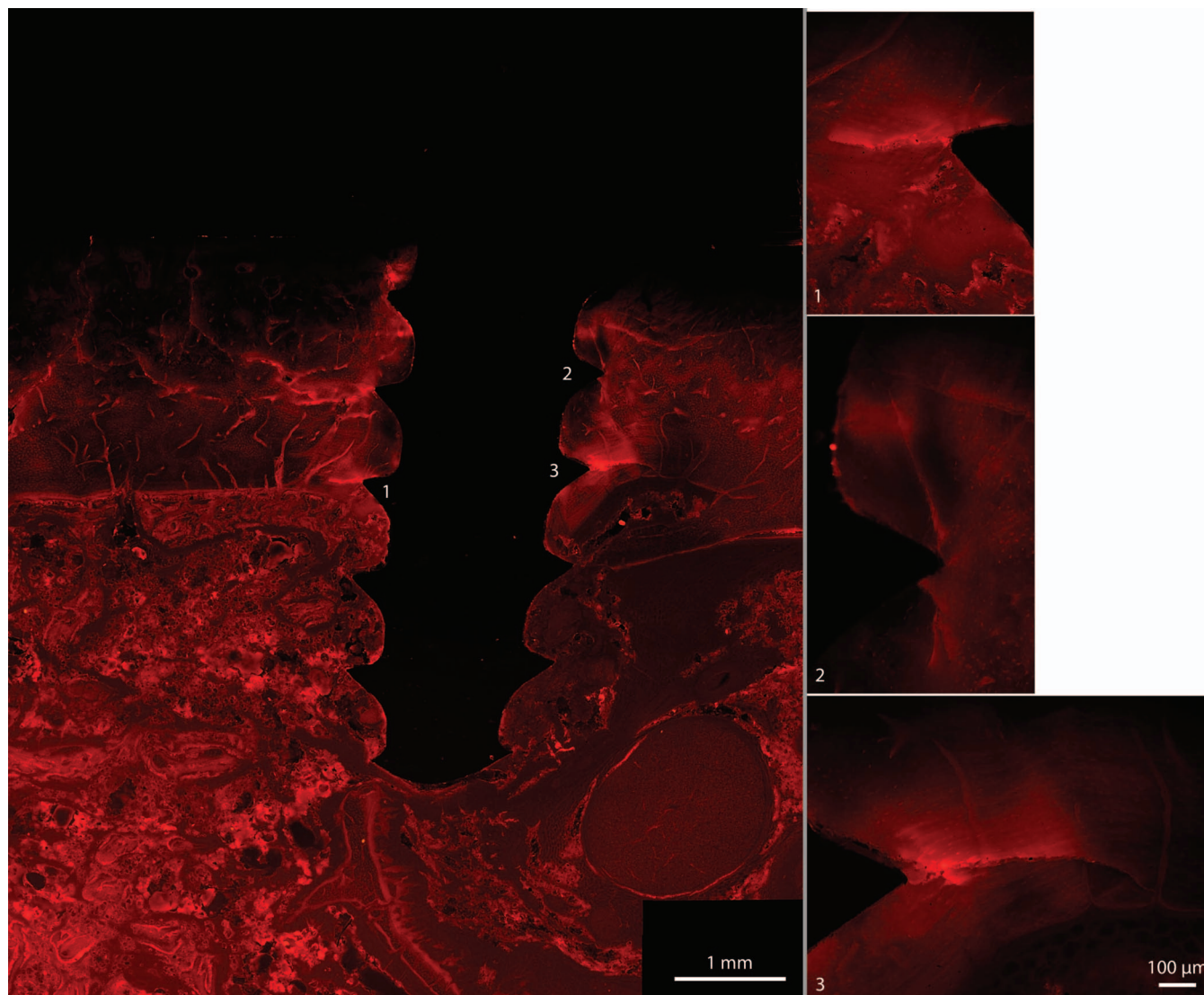


Figure 3. Cylindrical mini-screw implants, 2.0-mm diameter, with microdamage.

success rate is lower in the mandible without pilot drilling and the equal success rates in the two jaws with pilot drilling.⁴⁰ This suggests that pilot drilling is advisable when inserting MSIs into regions with dense or thick cortical bone.

Microdamage at different insertion sites within the maxilla and mandible was not analyzed because a previous study found no differences in MSI insertion associated microdamage in different sites within the same jaw.²⁸ A clinical study demonstrated that a higher failure rate occurs when inserting MSIs in posterior mandibular areas with high bone density and cortical thickness compared to the maxillary posterior area.⁴⁰ This may be attributed to overtightening or excessive insertion torque causing overheating, poor primary stability, inflammation, or local disturbances that prevent normal healing.⁷ Furthermore, an ideal study

design should include a standardized insertion torque (<10 Ncm).¹² More experimental and clinical studies are needed to better assess the complex relationships between mechanical factors, clinical techniques and MSI adjacent bone response.

CONCLUSIONS

- With the same size pilot hole, large diameter cylindrical MSIs create more microdamage than small diameter cylindrical MSIs.
- Pilot drilling effectively reduces microdamage with tapered MSIs, especially those with larger diameters.
- Inserting a large diameter cylindrical MSI is not recommended because it may generate excessive microdamage.
- Pilot drilling effectively reduces microdamage with MSIs in the mandible.

Table 5. Comparison of Cortical Thickness, Implant Surface, and Microdamage Parameters Including Number of Cracks, Crack Length, Crack Density, and Total Microdamage Burden Per Surface Length Between Cylindrical and Tapered Mini-screw Implants With the Same Diameter

Mini-screw Implant	Cortical Thickness, μm		Implant Surface, μm		Number of Cracks		Crack Length, μm		Crack Density (Number of Cracks/ μm) $\times 10^{-3}$		Total Microdamage Burden Per Surface Length, $\mu\text{m}/\mu\text{m}$	
	Mean		Mean		Mean		Mean		Mean		Mean	
	Standard Error	P Value	Standard Error	P Value	Standard Error	P Value	Standard Error	P Value	Standard Error	P Value	Standard Error	P Value
1.6 mm												
Cylindrical	1956.35 (143.30)	.419	6512.22 (805.44)	.003*	5.33 (0.88)	.873	260.02 (26.88)	.946	0.78 (0.20)	.008*	0.21 (0.07)	.117
Tapered	1831.22 (144.06)		4877.98 (807.67)		5.46 (0.88)		262.43 (27.01)		1.24 (0.20)		0.30 (0.07)	
2.0 mm												
Cylindrical	1936.89 (140.51)	.341	6327.11 (800.71)	.002*	7.64 (0.86)	.009*	362.33 (25.85)	.001*	1.27 (0.20)	.710	0.46 (0.07)	.004*
Tapered	1792.36 (143.87)		4627.11 (806.74)		5.38 (0.88)		244.39 (27.02)		1.21 (0.20)		0.31 (0.07)	

* Statistical significance ($P < .05$).

REFERENCES

1. Creekmore TD, Eklund MK. The possibility of skeletal anchorage. *J Clin Orthod.* 1983;17:266–269.
2. Kanomi R. Mini-implant for orthodontic anchorage. *J Clin Orthod.* 1997;31:763–767.
3. Kyung HM, Park HS, Bae SM, Sung JH, Kim IB. Development of orthodontic micro-implants for intraoral anchorage. *J Clin Orthod.* 2003;37:321–328; quiz 14.
4. Liou EJ, Pai BC, Lin JC. Do miniscrews remain stationary under orthodontic forces? *Am J Orthod Dentofacial Orthop.* 2004;126:42–47.

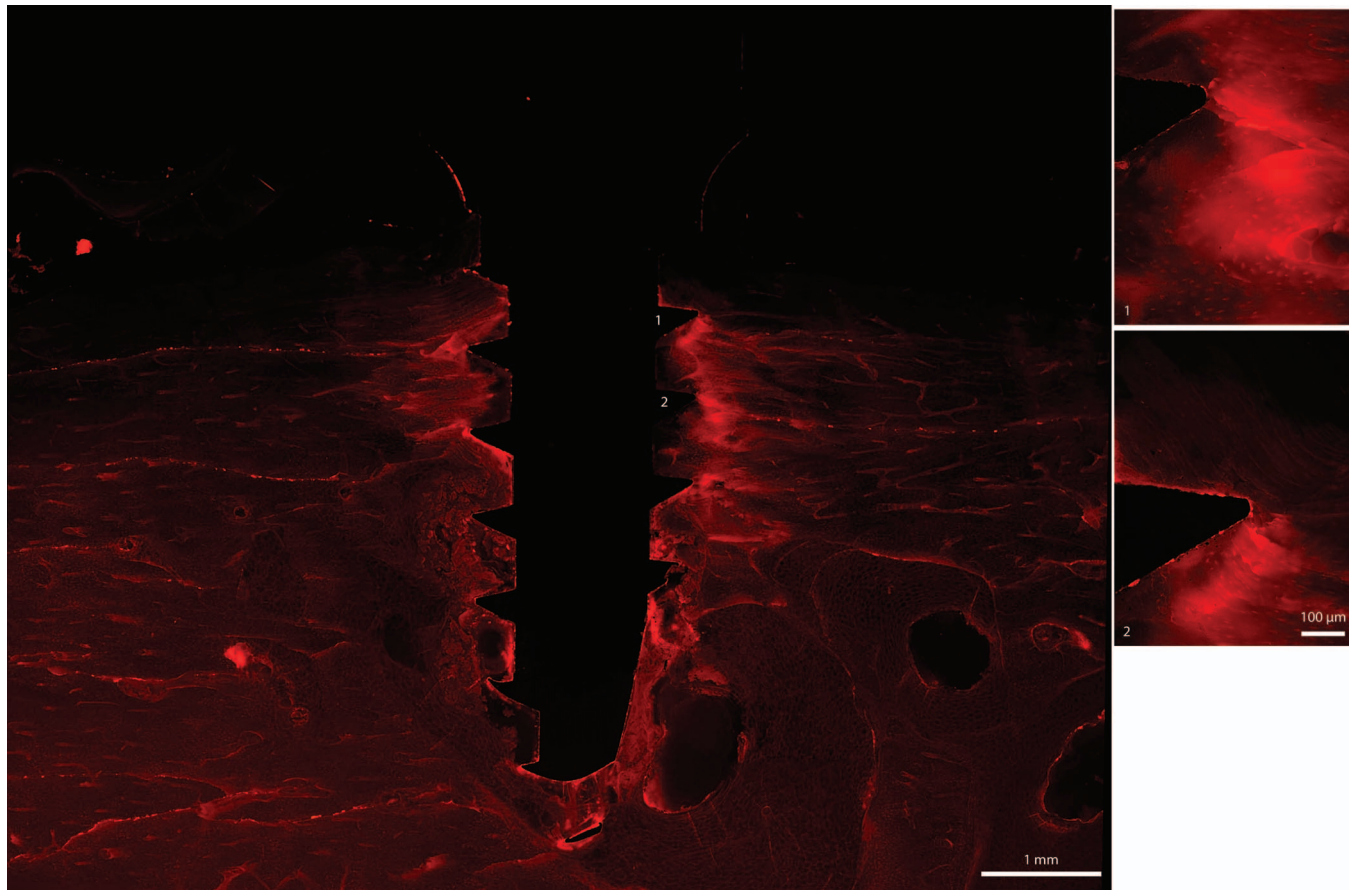


Figure 4. Tapered mini-screw implants, 2.0-mm diameter, with microdamage.

Table 6. Comparison of Cortical Thickness, Implant Surface, and Microdamage Parameters Including Number of Cracks, Crack Length, Crack Density, and Total Microdamage Burden Per Surface Length Between the Maxilla and Mandible Inserted With 1.6-mm and 2.0-mm Cylindrical and Tapered Mini-screw Implants With the Same Shape

	Cortical Thickness, μm		Implant Surface, μm		Number of Cracks		Crack Length, μm		Crack Density (Number of Cracks/ μm) $\times 10^{-3}$		Total Microdamage Burden Per Surface Length, $\mu\text{m}/\mu\text{m}$	
	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value	Mean Standard Error	<i>P</i> Value
1.6 mm												
Maxilla	1517.78 (139.79)	<.001*	4642.69 (795.37)	<.001*	4.73 (0.86)	.065	259.11 (26.72)	.897	1.12 (0.20)	.094	0.28 (0.06)	.178
Mandible	2269.79 (136.01)		6747.51 (788.20)		6.06 (0.84)		263.33 (25.46)		0.89 (0.20)		0.22 (0.06)	
2.0 mm												
Maxilla	1571.99 (139.80)	<.001*	4469.31 (795.38)	<.001*	4.94 (0.86)	<.001*	314.11 (26.72)	.501	1.04 (0.20)	.519	0.37 (0.06)	.570
Mandible	2157.26 (132.86)		6484.91 (782.35)		8.07 (0.82)		292.61 (24.40)		1.29 (0.19)		0.39 (0.06)	
Cylindrical												
Maxilla	1489.09 (138.29)	<.001*	5019.73 (792.91)	<.001*	4.99 (0.85)	<.001*	333.13 (26.11)	.170	1.02 (0.20)	.959	0.35 (0.06)	.418
Mandible	2404.15 (136.69)		7819.6 (790.86)		7.98 (0.84)		289.22 (25.29)		1.03 (0.20)		0.32 (0.06)	
Tapered												
Maxilla	1600.68 (144.27)	.002*	4092.27 (805.49)	.003*	4.68 (0.88)	.043*	240.10 (27.76)	.419	1.30 (0.20)	.268	0.30 (0.07)	.985
Mandible	2022.90 (134.96)		5412.82 (786.72)		6.16 (0.84)		266.72 (24.98)		1.15 (0.20)		0.30 (0.06)	

* Statistical significance ($P < .05$).

- Melsen B. Mini-implants: where are we? *J Clin Orthod.* 2005;39:539–547; quiz 31–32.
- Lee JS, Kim JK, Park YH, Vanarsdall RL Jr. *Applications of Orthodontic Mini-Implants.* Hanover Park, Ill: Quintessence Publishing Co Inc; 2007.
- Melsen B, Costa A. Immediate loading of implants used for orthodontic anchorage. *Clin Orthod Res.* 2000;3:23–28.
- Crismani AG, Bertl MH, Celar AG, Bantleon HP, Burstone CJ. Miniscrews in orthodontic treatment: review and analysis of published clinical trials. *Am J Orthod Dentofacial Orthop.* 2010;137:108–113.
- Takaki T, Tamura N, Yamamoto M, et al. Clinical study of temporary anchorage devices for orthodontic treatment—stability of micro/mini-screws and mini-plates: experience with 455 cases. *Bull Tokyo Dent Coll.* 2010;51:151–163.
- Park HS, Jeong SH, Kwon OW. Factors affecting the clinical success of screw implants used as orthodontic anchorage. *Am J Orthod Dentofacial Orthop.* 2006;130:18–25.
- Wilmes B, Drescher D. Impact of insertion depth and predrilling diameter on primary stability of orthodontic mini-implants. *Angle Orthod.* 2009;79:609–614.
- Motoyoshi M, Hirabayashi M, Uemura M, Shimizu N. Recommended placement torque when tightening an orthodontic mini-implant. *Clin Oral Implants Res.* 2006;17:109–114.
- Kim JW, Baek SH, Kim TW, Chang YI. Comparison of stability between cylindrical and conical type mini-implants. Mechanical and histological properties. *Angle Orthod.* 2008;78:692–698.
- O'Sullivan D, Sennerby L, Meredith N. Influence of implant taper on the primary and secondary stability of osseointegrated titanium implants. *Clin Oral Implants Res.* 2004;15:474–480.
- Motoyoshi M, Hirabayashi M, Uemura M, Shimizu N. Recommended placement torque when tightening an orthodontic mini-implant. *Clin Oral Implants Res.* 2006;17:109–114.
- Wawrzinek C, Sommer T, Fischer-Brandies H. Microdamage in cortical bone due to the overtightening of orthodontic microscrews. *J Orofac Orthop.* 2008;69:121–134.
- Lee NK, Baek SH. Effects of the diameter and shape of orthodontic mini-implants on microdamage to the cortical bone. *Am J Orthod Dentofacial Orthop.* 2010;138:8.e1–8; discussion 8–9.
- Chen CH, Chang CS, Hsieh CH, et al. The use of microimplants in orthodontic anchorage. *J Oral Maxillofac Surg.* 2006;64:1209–1213.
- Kim KH, Chung C, Yoo HM, Park DS, Jang IS, Kyung SH. The comparison of torque values in two types of miniscrews placed in rabbits: tapered and cylindrical shapes—preliminary study. *Korean J Orthod.* 2011;41:280–287.
- Wilmes B, Rademacher C, Olthoff G, Drescher D. Parameters affecting primary stability of orthodontic mini-implants. *J Orofac Orthop.* 2006;67:162–174.
- Heo YY, Cho KC, Baek SH. Angled-predrilling depth and mini-implant shape effects on the mechanical properties of self-drilling orthodontic mini-implants during the angled insertion procedure. *Angle Orthod.* 2012;82:881–888.
- Kim YK, Kim YJ, Yun PY, Kim JW. Effects of the taper shape, dual-thread, and length on the mechanical properties of mini-implants. *Angle Orthod.* 2009;79:908–914.

23. Hong C, Lee H, Webster R, et al. Stability comparison between commercially available mini-implants and a novel design: part 1. *Angle Orthod.* 2011;81:692–699.
24. Song YY, Cha JY, Hwang CJ. Mechanical characteristics of various orthodontic mini-screws in relation to artificial cortical bone thickness. *Angle Orthod.* 2007;77:979–985.
25. Duaibis R, Kusnoto B, Natarajan R, Zhao L, Evans C. Factors affecting stresses in cortical bone around miniscrew implants. *Angle Orthod.* 2012;82:875–880.
26. Singh S, Mogra S, Shetty VS, Shetty S, Philip P. Three-dimensional finite element analysis of strength, stability, and stress distribution in orthodontic anchorage: a conical, self-drilling miniscrew implant system. *Am J Orthod Dentofacial Orthop.* 2012;141:327–336.
27. Yadav S, Upadhyay M, Liu S, et al. Microdamage of the cortical bone during mini-implant insertion with self-drilling and self-tapping techniques: a randomized controlled trial. *Am J Orthod Dentofacial Orthop.* 2012;141:538–546.
28. Liu SS, Cruz-Marroquin E, Sun J, Stewart KT, Allen MR. Orthodontic mini-implant diameter does not affect in-situ linear microcrack generation in the mandible or the maxilla. *Am J Orthod Dentofacial Orthop.* 2012;142:768–773.
29. Huja SS, Katona TR, Burr DB, Garetto LP, Roberts WE. Microdamage adjacent to endosseous implants. *Bone.* 1999;25:217–222.
30. Frost HM. The regional acceleratory phenomenon: a review. *Henry Ford Hosp Med J.* 1983;31:3–9.
31. Frost HM. Some ABC's of skeletal pathophysiology. 5. Microdamage physiology. *Calcif Tissue Int.* 1991;49:229–231.
32. Frost HM. A brief review for orthopedic surgeons: fatigue damage (microdamage) in bone (its determinants and clinical implications). *J Orthop Sci.* 1998;3:272–281.
33. Burr D. Microdamage and bone strength. *Osteoporos Int.* 2003;14(suppl 5):S67–72.
34. Burr DB, Forwood MR, Fyhrie DP, et al. Bone microdamage and skeletal fragility in osteoporotic and stress fractures. *J Bone Miner Res.* 1997;12:6–15.
35. Burr DB, Turner CH, Naick P, et al. Does microdamage accumulation affect the mechanical properties of bone? *J Biomech.* 1998;31:337–345.
36. Cho KC, Baek SH. Effects of predrilling depth and implant shape on the mechanical properties of orthodontic mini-implants during the insertion procedure. *Angle Orthod.* 2012;82:618–624.
37. Gantous A, Phillips JH. The effects of varying pilot hole size on the holding power of miniscrews and microscrews. *Plast Reconstr Surg.* 1995;95:1165–1169.
38. Heidemann W, Gerlach KL, Grobel KH, Kollner HG. Influence of different pilot hole sizes on torque measurements and pullout analysis of osteosynthesis screws. *J Craniomaxillofac Surg.* 1998;26:50–55.
39. Park J, Cho HJ. Three-dimensional evaluation of interradiolar spaces and cortical bone thickness for the placement and initial stability of microimplants in adults. *Am J Orthod Dentofacial Orthop.* 2009;136:314.e1-12; discussion 14–15.
40. Cheng SJ, Tseng IY, Lee JJ, Kok SH. A prospective study of the risk factors associated with failure of mini-implants used for orthodontic anchorage. *Int J Oral Maxillofac Implants.* 2004;19:100–106.