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Effects of insertion angle and implant thread type on the fracture properties of orthodontic mini-implants during insertion

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조 일 식

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- ABSTRACT -

Effects of insertion angle and implant thread type on the fracture properties of orthodontic mini-implants during insertion

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OBJECTIVE: To investigate the effects of insertion angle and implant thread type on the fracture properties of orthodontic mini-implants (OMIs) during the insertion procedure.

MATERIALS AND METHODS: A total of 100 OMIs (self-drilling type, cylindrical shape, 11 mm in length, 1.5 mm in diameter; Biomaterials Korea Inc.) were allocated into ten groups according to thread type (dual and single) and insertion angle (0°, 8°, 13°, 18°, and 23°; N=10 per group). The OMIs were installed in artificial bone blocks that simulated the cortical and cancellous bone (Sawbone®, Pacific Research Laboratories Inc.), root (polymethylmethacrylate stick), and periodontal ligament (Imprint II Garant light body, 3M–ESPE). Maximum insertion torque (MIT), total insertion energy (TIE), and peak time (PT) were measured and analyzed statistically. Frequency of fracture and deformation of OMIs was statistically analyzed.

RESULTS: There were significant differences in MIT, TIE, and PT among the different IAs and threads (all $P < .001$). When IA increased, MIT increased in both thread groups. However, TIE and PT did not show significant differences among 0°, 8°, and 13° IAs in the dual thread group or 8°, 13°, and 18° IAs in the single thread group. The dual thread groups showed higher MIT at all IAs, higher TIE at 0° and 23° IAs, and longer PT at a 23° IA than the single thread groups. In the 0°, 8°, and 13° IA groups, none of the OMIs fractured or became deformed. However, in the 18° IA group, all the OMIs were fractured or deformed. Dual thread OMIs showed more fracturing than deformation compared to single thread OMIs ($P < .01$). In the 23° IA group, all OMIs penetrated the artificial root without fracturing and deformation.

CONCLUSION: When OMIs contact artificial root at a critical contact angle, the deformation or fracture of OMIs can occur at lower MIT values than those of penetration. The thread type can influence the fracture ratio in the critical insertion angle. The results of this study might provide a guideline for further studies or clinical situations.

Key words: Fracture properties, Mini–implant, Insertion angle, Implant thread type

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I. Introduction

The use of orthodontic mini−implants (OMIs) for anchorage purpose has greatly broadened the treatment scope of orthodontics during the last 10 years. Although OMIs have advantages such as the reduced necessity of patient compliance and the simplification of treatment mechanics, they sometimes can fail because of a variety of reasons including age, sex, degree of peri−implant inflammation, mobility, OMI fracture, root proximity, and root contact.[1−4]

If the OMI is placed in the area of the narrow inter−dental space, iatrogenic root injury can be occurred. Potential complications of root injury mentioned in the literature include loss of tooth vitality, osteosclerosis, and dentoalveolar ankylosis.[5−7] Iatrogenic root damage from OMIs is an important issue but has, until recently, received little attention. Asscherickx et al.[1] suggested that proximity or contact between the OMI and the root might be major risk factors for OMIs failure. In their animal studies, Kim and Kim[8] observed that when OMIs were left *in situ*, the root surface mostly resorbed away from the OMI thread and partial repair started at eight weeks. They also found that when the OMI thread was left touching the root, the normal healing response did not occur.[8]

OMI fracture might be a more severe clinical complication than root contact.[9] In order to reduce the fracture risk of OMIs, their diameter can be increased, resulting in an increase in fracture torque.[10,11] However, there have been no studies evaluating the effects of OMI insertion angle and thread type on its fracture properties. Therefore, the purpose of this *in vitro* study was to investigate the effects of insertion angle and implant thread type on the fracture properties of OMI during the insertion procedure in artificial bone blocks that simulated the cortical and cancellous bone, root, and periodontal ligament space in humans.

II. REVIEW OF LITERATURE

1. The success of orthodontic mini-implants(OMIs)

The range of success rate of orthodontic mini-implants(OMIs) have been reported as 84% to 92%.[3,12-17,27] Orthodontic mini-implants (OMIs) stability is known to be associated with host factors (age, gender, skeletal pattern, oral hygiene, and inflammation), bone quality (thickness and stiffness), design of OMI (shape and diameter), and insertion and loading modality of OMI (implantation location, type of placement surgery, and immediate loading).[16,18-24,27] Therefore, it is necessary to investigate design and insertion modality of OMIs for improving OMI stability.[16,19-24,27]

In former studies, there were numerous opinions about the relationship between root contact or proximity and success rate of OMIs. Asscherickx et al.[1] suggested that root contact and marginal position could be major risk factors for OMI failure. And, Kuroda et al.[2] insisted that the proximity of OMIs to the root is one of the major risk factors for the failure of screw anchorage. Liou et al.[25] advocated that OMIs could be placed in a non-tooth-bearing area where has no anatomical structure, or in a tooth−bearing area with 2 mm of safety clearance between the OMI and dental root. However, Kim et al.[26] proclaimed that root proximity alone is not a major risk factor for OMIs failure.

Kim et al.[19] and Kim et al.[27] reported that the dual thread OMI provided more improved mechanical stability and higher removal torque value than the single thread OMI. Kim et al.[19] suggested OMIs that had the dual thread on the upper part of the thread could be less harmful to the alveolar bone. However, the dual thread OMI had the weakness of the long insertion time.[19]

2. Parameters assessing the stability of OMIs

Motoyoshi et al.[16] suggested to use the maximum insertion torque (MIT) to explain the success rate of OMIs. They reported that there was no significant difference in the success rate among locations of OMIs, age, and gender. However, too high or low MIT can be influenced the success rate of OMIs.[16] They recommended that the MIT should be within the range from 5 to 10 Ncm to obtain higher success rate.[16]

In contrast to dental implant, most of OMIs are self−drilling type.

Therefore, OMIs continuously compress the alveolar bone during the insertion procedure. Since the MIT was only the maximum value of the insertion procedure, the MIT alone has a limitation to explain the success rate.

Several recent studies have used the total insertion energy (TIE) as the reference value for predicting the stability of OMIs.[28-31] Salmoria et al.[32] insisted that the insertion torque is not an efficient method for predicting the stability of OMIs. Previous studies[28-31] suggested that since OMI stability can be influenced by the degree of compression stress in the bone, it is reasonable to consider both the MIT and the TIE as reference values for predicting the OMI stability. TIE is the sum of the insertion torque values from the beginning to the end of OMI installation.

3. In vitro study using artificial bone blocks

The artificial bone block was commonly used to evaluate the mechanical property of OMIs.[19,20,28-30,33] Kim et al.[19] used the single layer artificial bone block. However, since the human alveolar bone consisted with cortical and cancellous bone, their study[19] had a limitation in nature. The subsequent studies[20,28-30,33] used artificial bone blocks consisted of two layers identical to human condition.

Some studies[20,33] used E−glass−filled epoxy sheets (1.7 g/cc) and solid rigid polyurethane foam (0.64 g/cc) to simulate the cortical bone and the cancellous bone. However, the density of these artificial bones was too higher compared to human bone. As a result, the MIT values were higher than the values in human study.[16] To simulate the identical human condition, recent previous studies[28−30] have used solid rigid poly urethane foams with densities as follows: a density of 50 pcf (0.8 g/cc) for the cortical bone and a density of 30 pcf (0.48 g/cc) for the cancellous bone.

III. MATERIALS AND METHODS

OMIs and allocation of the groups

A total of 100 OMIs (self-drilling type, cylindrical shape, 11 mm in length, ASTM F-136 grade V, Ti-6Al-4V; Biomaterials Korea Inc., Seoul, Korea) were allocated into ten groups according to the OMI thread type (dual and single thread, Figure 1) and insertion angle (0°, 8°, 13°, 18°, and 23°; N = 10 per group). All of the OMIs had an external diameter of 1.45 mm and an internal diameter of 1.0 mm. Dual thread OMIs had the dual thread on the upper part of the thread (Figure 1).

Artificial bone block

The custom-made polyurethane foam artificial bone blocks consisted of two layers that simulated the cortical and cancellous bone [180 mm in length, 15 mm in width, and 18 mm in height; the upper layer with a density of 0.80 g/cc (50 pcf) and height in 3 mm; the lower layer with a density of 0.48 g/cc (30 pcf) and height in 15mm, Sawbone®, Pacific Research Laboratories Inc., Vashon, WA, USA; Table 1 and Figure 2].

Artificial root

The artificial root was made using a transparent round polymethylmetacylate stick (PMMA, density 1.19 g/cc, tensile strength 72 Mpa, compressive strength 123 Mpa) with a 10mm diameter. To simulate the periodontal ligament space, a 10.5 mm diameter hole was drilled into the artificial bone blocks. The PMMA stick was then inserted into the artificial bone blocks with silicone impression materials (Imprint II Garant light body, 3M ESPE, St. Paul, USA).[34,35]

Placement of OMIs

We used an artificial bone block with 3 mm of cortical bone to simulate the mandibular molar area. The sum of the cortical bone (3 mm), cancellous bone (1 mm), and radius of the artificial root (5 mm) in the midline was 9 mm (Figure 2). Therefore, to clearly determine the effect of root contact with the OMI, 11 mm OMIs were used.

After the custom-made polyurethane foam artificial bone block was fixed with a metal clamp, the OMIs were installed in the block using a driving torque tester (Biomaterials Korea Inc., Figure 3). The tester was set to a uniform speed of 28 rpm. A 500 g weight was added on the tester's rotational axis to mimic the perpendicular force in a clinical situation.

The pilot tests were performed to determine the specific insertion angle that OMI would touch with the periodontal ligament space made by the silicone impression materials in the given dimension (Figure 2). This was determined as 8° insertion angle, the insertion angle was then increased with interval of 5°, from 8° to 23°. The control was set as 0° insertion angle. These different insertion angles (0°, 8°, 13°, 18°, and 23°) were applied using a custom-made vise (Figure 3).

Measurements of the Insertion Variables and Grinding Procedure of the Samples

The insertion variables analyzed were maximum insertion torque, total insertion energy, and peak time. The definitions of these variables are given in Figure 4. After the variables were measured, all samples were ground with a model trimmer to evaluate the status of the OMIs.

Statistical Analysis of the Insertion Variables

The sample size determination was performed by a power analysis using the Sample Size Determination Program version 2.0.1 (Seoul National University Dental Hospital, #2007-01-122-004453, Seoul, Korea). Welch variance weighted analysis of variance, Duncan's multiple comparison test, and the χ^2 test were performed for statistical analyses. The level of significance for all the tests was set at $P < .05$.

IV. Results

Comparison of the mechanical properties of OMIs in the artificial bone block during the insertion procedure

There were significant differences in maximum insertion torque, total insertion energy, and peak time among the IA and thread groups (all $P < .001$, Table 2). Dual thread groups showed higher maximum insertion torque values than single thread groups for all IAs. Although the 8° and 13° IA groups did not show significant differences within each thread group, maximum insertion torque showed a tendency to increase according to increases in the IA in both single and dual thread groups, respectively (Figure 5A). In terms of total insertion energy, the dual thread groups showed a significant increase at 18° and 23° IAs, and the single thread groups showed significant increases at 8° and 23° IAs. In other words, total insertion energy did not show a significant difference among the 0°, 8°, and 13° IAs in the dual thread groups and among the 8°, 13°, and 18° IAs in the single thread groups. The total insertion energy values of dual thread groups were significantly higher for 0° and 23° IAs than the single thread groups (Figure 5B). In terms of peak time, the 0°, 8°, and 13° IA groups did not show a significant difference within the dual thread groups. Within the single thread groups, the 8°, 13°, and 18° IAs did not show a significant difference. The peak time in single thread groups was significantly higher only in the 13° IA than in the dual thread groups, but the peak time within the dual thread groups was significantly higher only for the 23° IA than the single thread groups (Figure 5C).

Fracture ratio according to the thread type of OMIs

In the 0°, 8°, and 13° insertion angle groups, none of the OMIs were fractured or deformed (Figure 6). In the 23° insertion angle group, all of the OMIs penetrated the PMMA stick without fracturing or deformation (Figure 6).

However, in the 18° IA group, there was a significant difference in the occurrence of fracture and deformation according to the thread type ($P < .01$, Table 3). Eighty percent of dual thread OMIs were fractured and 90% of single thread OMIs were bent. In dual thread OMIs, the fracture sites were located at the dual thread site (Figure 6), while in single thread OMIs, the fracture sites were located at the end of thread (Figure 6).

Interestingly, the MIT values in the 18° insertion angle groups (deformation/fracture of OMIs) were smaller than those in the 23° insertion angle groups (root penetration) (30.6 Ncm vs. 34.8 Ncm for the dual thread type; 28.2 Ncm vs. 30.7 Ncm for the single thread type; Table 2). These findings indicate that OMIs can be deformed or broken at lower values compared to the values of penetration.

Time and torque graph

Irrespective of the IA and OMI thread type, the almost same patterns were observed among the groups until 24 seconds after insertion, when was just before contact with the artificial root (PMMA stick). After contact with the artificial roots, higher insertion angle and dual thread OMIs showed higher insertion torque values than lower IA and single thread OMIs (Figure 7). Especially in the 18° insertion angle group, dual thread OMIs showed higher insertion torque values than single thread OMIs (Figure 8).

V. Discussion

In this study, the same artificial bone that had been used in previous studies[29,30] was used to simulate cortical and cancellous bone. And, the transparent PMMA stick was used as an artificial root to simulate the human counterpart and to help identification of root contact or penetration by OMIs. Although the density of the PMMA stick (1.19 g/cc) was slightly lower than that reported in previous studies (1.27~1.50 g/cc)[36,37], the tensile strength was similar with the results of previous studies.[38,39]

Cho and Baek[29] reported that the MIT value measured in the same artificial bone block was 16.31 ± 0.32 Ncm, which was lower than that of the present study. This difference seems to have originated from the difference in the length of OMI studied (7 mm in Cho and Baek[29] vs. 11 mm in the present study). Kim et al.[40] also reported that longer OMIs showed higher MIT values.

In the 8° and 13° IA groups, there was no significant difference in the values of MIT, TIE, and PT because there were no deformations or fractures of the OMIs at the contact site with the PMMA stick (Figure 5).

However, these findings do not mean that slight root contact is safe. Kuroda et al.[41] and Chen et al.[42] suggested that proximity or contact between the OMI and the root is a major risk factor for the failure of the OMI. In addition, Lee et al.[43] reported that the incidence of root resorption increased when the distance between the OMI and the root was less than 0.6 mm, and that the incidence of bone resorption and ankylosis was increased when OMIs came close to root surfaces even without root contact.

Since all the OMIs showed deformations or fractures in the 18° IA group, regardless of thread type, an IA of 18° seemed to be a critical angle for slippage or penetration at the root contact site in this study. Interestingly, the thread type influenced the fracture ratio in the 18° IA group (80% fracture and 20% bending in the dual thread group vs 10% fracture and 90% bending in the single thread group, $P < .01$; Table 3). The reason for this result seems to originate from the differences in the structural and physical properties of the thread types. Dual thread OMIs exhibited a significant increase in total insertion energy at an 18° IA compared to a 13° IA (Table 2, Figure 5B). However, single thread OMIs did not show a significant increase in total insertion energy at 18° IA compared to 13° IA (Table 2, Figure 5B). In other words, there were differences in stress concentrations between dual and single thread OMIs. However, this result does not imply that single thread OMIs are superior to dual thread OMIs, because deformed OMIs also carry a risk of fracturing during removal.

At the beginning of root contact, the time/insertion torque graph showed higher values irrespective of the presence of deformation or penetration, which was in agreement with previous studies. Brisceno et al.[44] suggested that the insertion torque was twice as high in cases of root contact than those without root contact. Therefore, abrupt increase in resistance or insertion torque value during the OMI installation can be used as an indicator of possible root contact with the OMI.

Lima et al.[45] reported that fractures occurring at the moment of insertion, which have an incidence of around 4% in the literature, are principally due to excessive force and the inability of the implant to resist rotational forces. In the present study, deformation/fracture torque was lower than penetration torque (30.6 Ncm vs. 34.8 Ncm for the dual thread type; 28.2 Ncm vs. 30.7 Ncm for the single thread type, Table 2). The reason seems to be due to the presence of lateral force at the critical contact angle. When the OMIs were contact with root at the critical contact angle, the deformation or fracture of OMIs can occur at lower MIT values than expected. There is also a possibility that fracture will occur, similar to the effect during clinical insertion of OMIs.

This study was an *in vitro* test performed with artificial bone, root, and periodontal ligament space. Because this experimental system has some limitations with regard to the understanding of the effects of the complex root surface, further studies are required to take into consideration the three-dimensional morphology of the root.

VI. Conclusions

- When an OMI comes into contact with artificial root at the critical contact angle, deformation or fracture of the OMI can occur at lower maximum insertion torque values than those of penetration.
- The thread type can influence the fracture ratio in the critical insertion angle.
- Although this is an *in vitro* study of the effects of OMI contact with artificial root and periodontal ligament space on the fracture properties of OMIs, the results of this study might provide a guideline for further studies or clinical situations.

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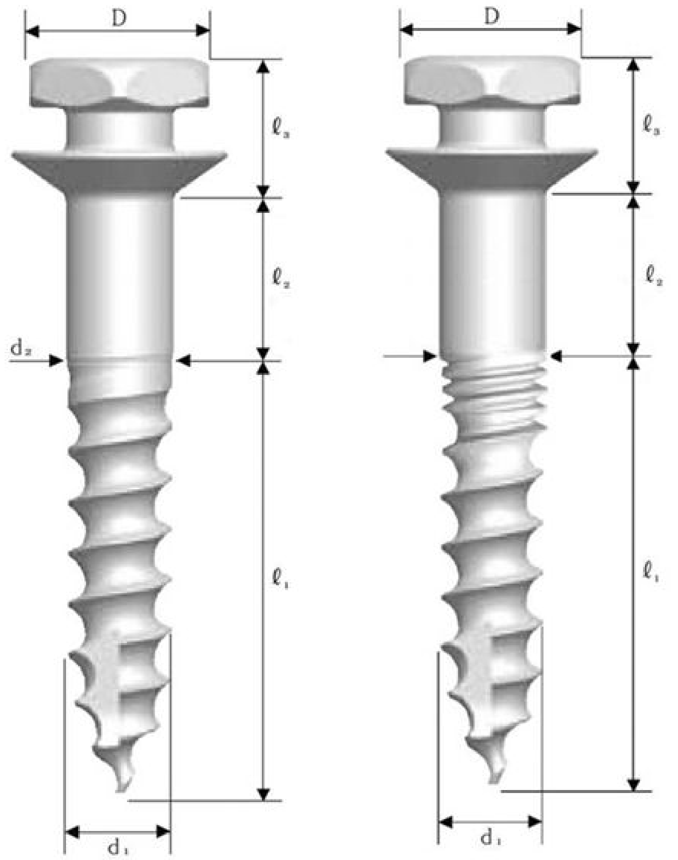

Size(mm)	d1	d2	l1	l2	l3	D
OAS-T1511	1.45	1.50	7.00	4.00	2.10	2.20
Mplant U3-11	1.45	1.50	7.00	4.00	2.10	2.20

Figure 1. Dimensions of orthodontic mini-implants [OMIs; single thread type (OAS-T1511 on the left side) and dual thread type (Mplant U3-11 on the right side), Biomaterials Korea Inc., Seoul, Korea] used in this study.

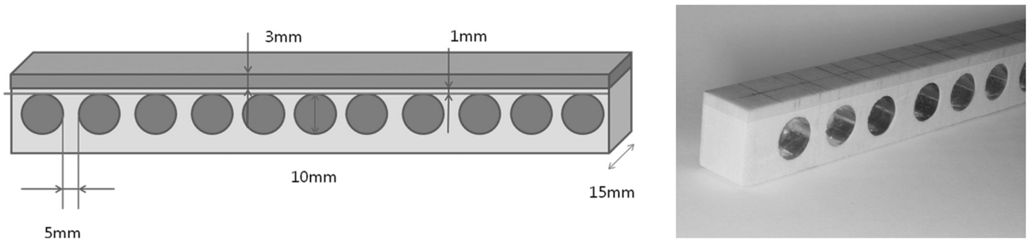

Figure 2. Diagram (left) and photograph (right) of the artificial bone block with two layers that simulated the cortical and cancellous bone (Sawbone®, Pacific Research Laboratories Inc., Vashon, WA, USA). A transparent polymethaylmethacrylate (PMMA) stick was placed into the artificial bone block with silicone impression materials (Imprint II Garant light body, 3M ESPE, St. Paul, USA) to simulate the root and periodontal ligaments.

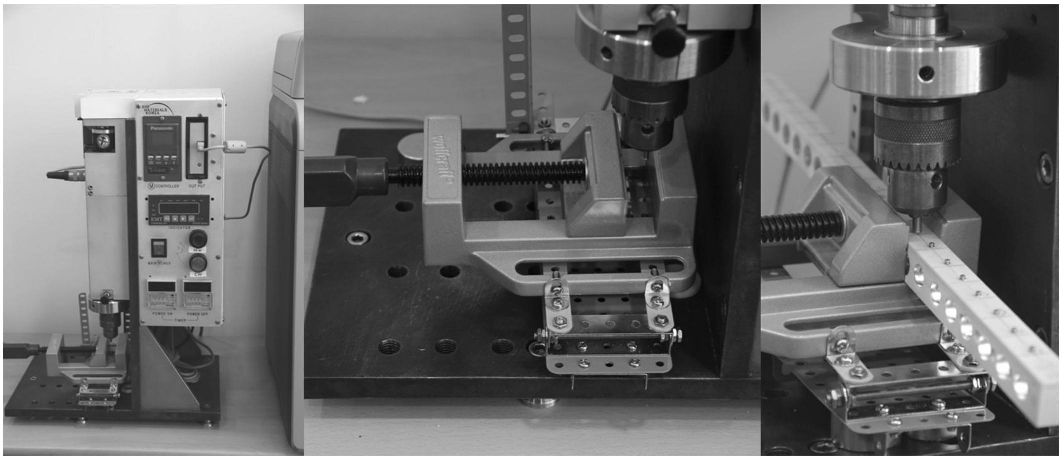

Figure 3. Driving torque tester (Biomaterials Korea Inc., Seoul, South Korea) and custom-made vise device.

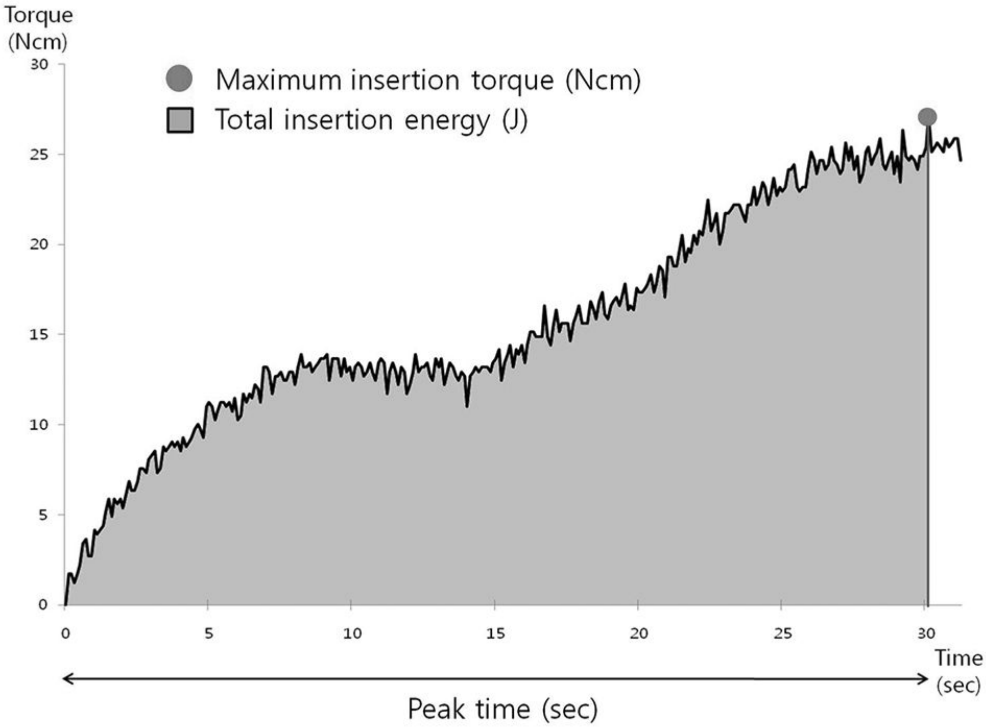

Figure 4. Definitions of the insertion variables. Peak time (seconds) is the time from the beginning of OMI insertion to the maximum insertion torque. Maximum insertion torque (Ncm) is the maximum torque value during OMI insertion. Total insertion energy (J) is calculated by the area under the graph from the beginning of OMI insertion to the maximum insertion torque.

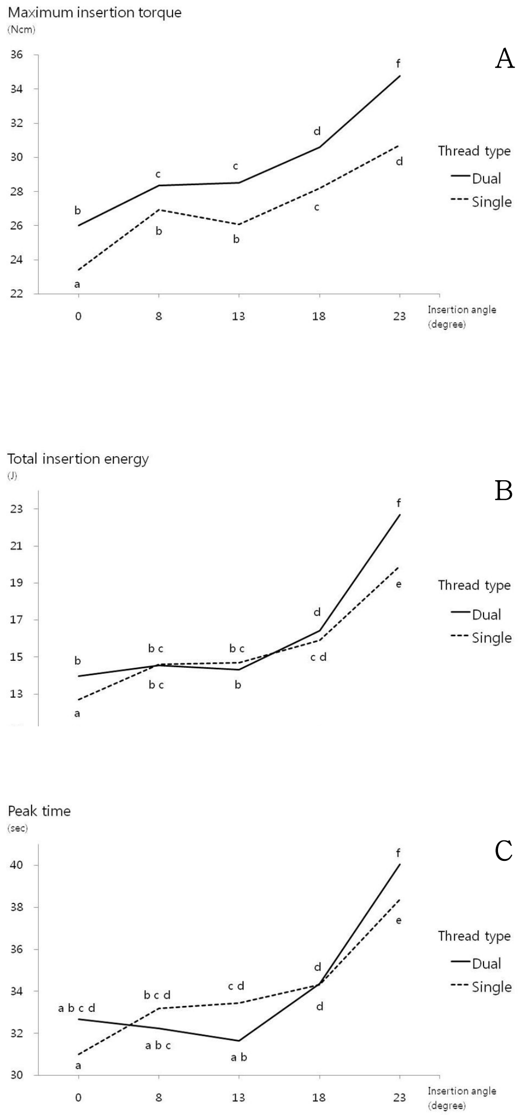

Figure 5. The results of the Duncan' s multiple comparison test between insertion angle and thread type. A. Maximum insertion torque; B. Total insertion energy; C. Peak time. The same letter indicate the groups that were not statistically different ($P > .05$).

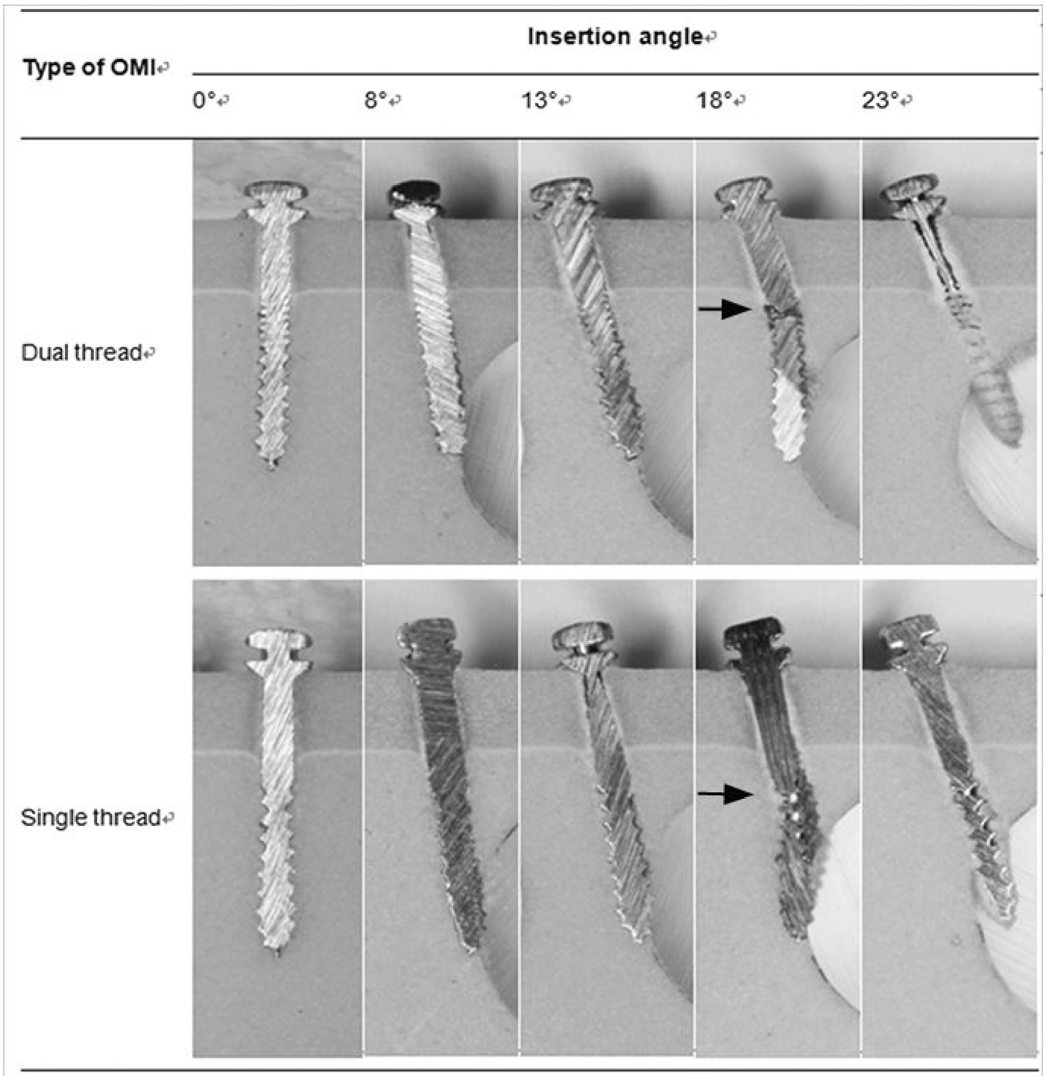

Figure 6. Cross−sectional view of installed OMIs according to insertion angle and thread type. The arrow shows the site of the OMI fracture or deformation.

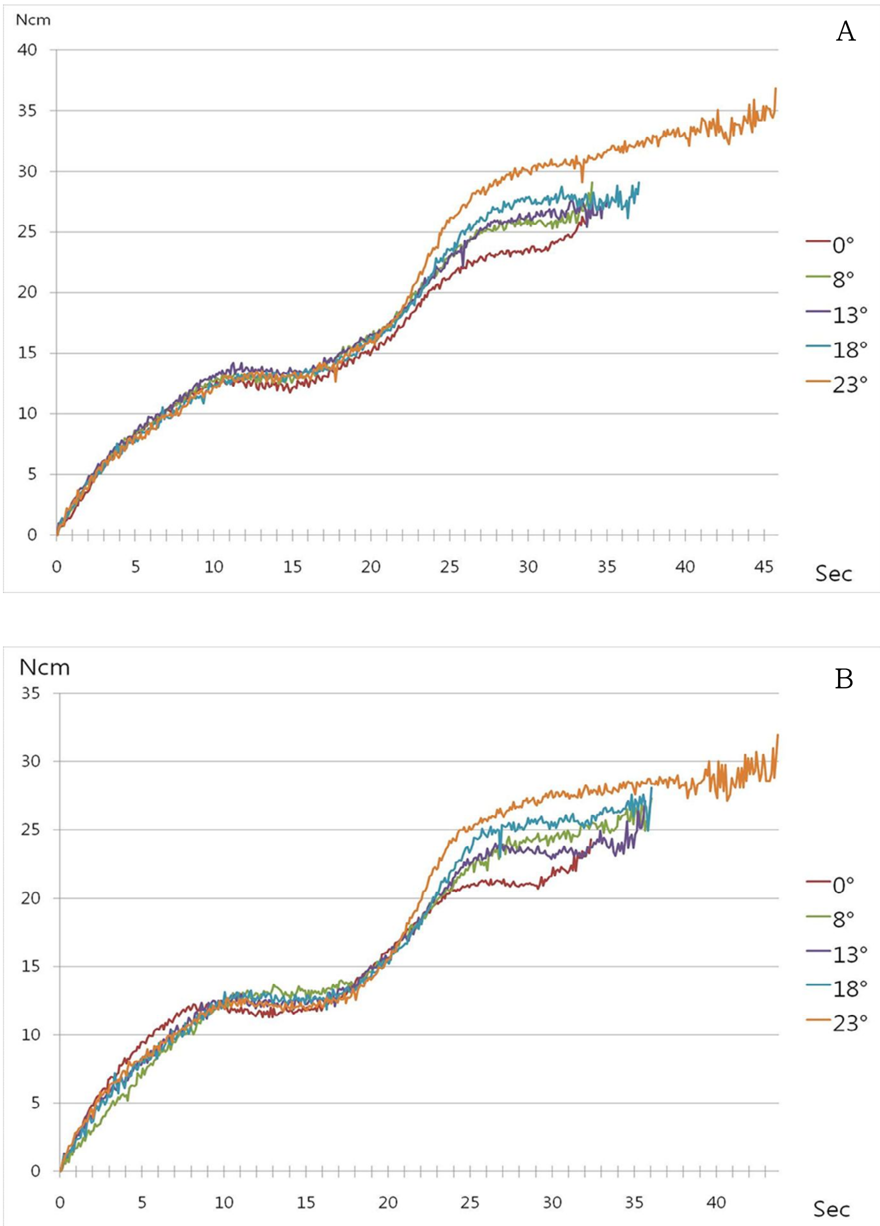

Figure 7. Superimposition of time−insertion torque graphs between the 0°, 8°, 13°, 18°, and 23° insertion angle groups. A. Dual thread OMIs; B. Single thread OMIs.

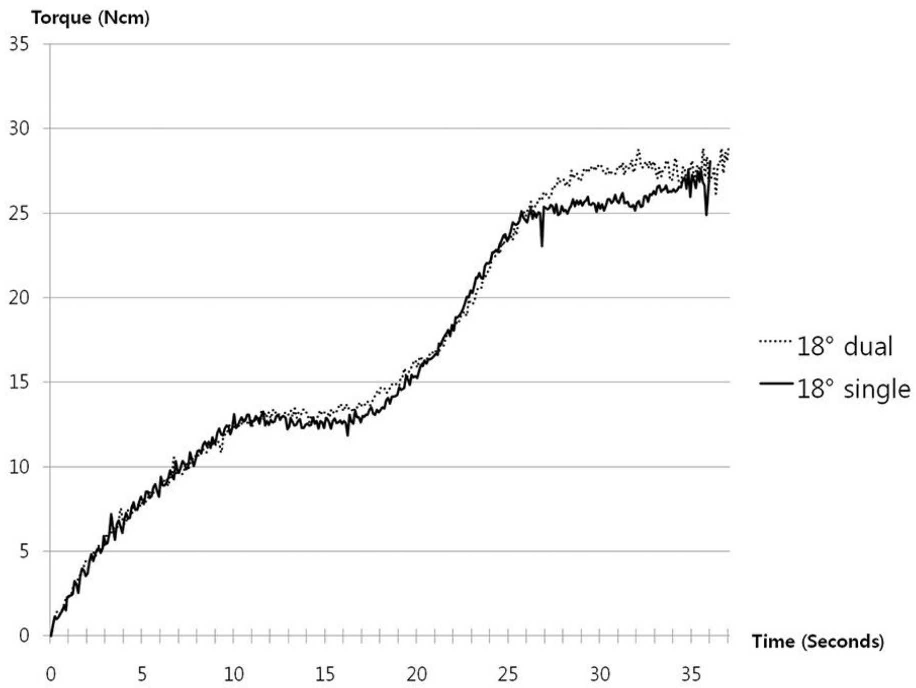

Figure 8. Superimposition of the time−insertion torque graph between the 18˚ dual and single thread OMI groups.

Table 1. Mechanical properties of the polyurethane foam (Sawbones®, Pacific Research Laboratories Inc., Vashon, WA, USA) and the polymethylmetacylate(PMMA) stick used in the artificial bone block and the artificial root

	Density		Compressive		Tensile	
	(pcf)	(g/cc)	Strength (MPa)	Modulus (MPa)	Strength (MPa)	Modulus (MPa)
Cortical layer	50	0.80	58	1400	32	2000
Cancellous layer	30	0.48	19	520	12	427
Artificial root	–	1.19	123	–	72	–

Table 2. Comparison of the peak time, maximum insertion torque, and total insertion energy between groups

Insertion angle	Thread type (N = 10 per group)	Maximum insertion torque (Ncm)	Total insertion energy (J)	Peak time (sec)
0°	Dual	26.03 ± 1.16	13.98 ± 0.99	32.67 ± 0.83
	Single	23.44 ± 0.83	12.70 ± 0.72	31.01 ± 0.89
8°	Dual	28.34 ± 1.01	14.54 ± 0.81	32.23 ± 1.41
	Single	26.93 ± 1.48	14.62 ± 0.75	33.19 ± 1.78
13°	Dual	28.52 ± 0.73	14.33 ± 1.57	31.64 ± 2.14
	Single	26.07 ± 1.10	14.69 ± 0.69	33.45 ± 1.20
18°	Dual	30.59 ± 1.94	16.41 ± 0.93	34.37 ± 1.66
	Single	28.20 ± 0.91	15.90 ± 1.53	34.32 ± 1.35
23°	Dual	34.77 ± 1.37	22.68 ± 3.04	40.06 ± 3.37
	Single	30.74 ± 1.00	19.93 ± 1.53	38.38 ± 2.13
Significance		< 0.001 ***	< 0.001 ***	< 0.001 ***

Welch variance weighted ANOVA test was performed. *** represents $P < 0.001$

Table 3. The fracture ratio according to the thread type of the OMIs at an 18° insertion angle

Type of mini-implant	Fracture ratio (%)	Bending ratio (%)	*P* value
Dual thread (n = 10)	80	20	0.005 **
Single thread (n=10)	10	90	

χ^2 test was performed. ** represents $P < .01$.

In the 8° and 13° insertion angle groups, none of the OMIs were fractured or deformed.

In the 23° insertion angle group, all of the OMIs penetrated the artificial root (transparent polymethaylmethacrylate stick).

국문초록

교정용 미니임플랜트의 식립 각도 및 나사산 모양에 따른 파절 양상 분석

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연구목적

본 연구는 교정용 미니임플랜트의 식립 과정 중 식립 각도와 상부나사산의 구조에 따른 파절 양상을 분석하기 위한 것이다.

연구 재료 및 방법

총 100개의 교정용 미니임플랜트(자가 드릴링 형태, 원통형, 길이 11 mm, 직경 1.5 mm; Biomaterials Korea Inc.)를 상부 나사산의 형태(이중 및 단일 나사산) 및 식립 각도(0°, 8°, 13°, 18°, 23°)에 따라 총 10개 군으로 나누어 각 군당 10개 씩을 식립하였다. 교정용 미니임플랜트는 피질골과 수질골을 가상한 인조골(Sawbone®, Pacific Research Laboratories Inc.), 치근을 가상한 폴리메탈메타크릴레이트 봉, 치주 인대를 가상한 실리콘 인상재(Imprint II Garant light body, 3M-ESPE)에 식립하였다. 최대 식립 토크(Maximum insertion torque, MIT), 총 식립 에너지(Total insertion energy, TIE), 최대 식립 토크 도달 시간(Peak Time, PT)을 측정하여 통계분석을 시행하였으며, 교정용 미니임플랜트의 파절 및 변형 빈도 역시 통계적으로 분석하였다.

연구 결과

식립 각도와 상부 나사산의 형태에 따라 MIT, TIE, PT 값은 유의한 차이를 보였다($P < .001$). 두 상부 나사산 군 모두 식립 각도의 증가에 따라 MIT가 증가하였다. 그러나, 이중 나사산 군에서는 0°, 8°, 13° 군에서, 단일 나사산 군에서는 8°, 13°, 18° 군에서 MIT의 유의한 차이가 없었다. 이중 나사산 군은 단일 나사산 군에 비하여 모든 각도에서 더 높은 MIT를 보였으며, 0°와 23° 군에서 더 높은 TIE를, 23° 군에서 더 큰 PT를 보였다. 0°, 8°, 13° 군에서는 나사산의 종류에 관계없이 모든 교정용 미니임플랜트에서 파절이나 변형이 관찰되지 않았으나 18° 군에서는 모든 교정용 미니임플랜트에서 파절이나 변형이 관찰되었다. 이중 나사산 군의 경우 단일 나사산에 비하여 더 많은 파절이 나타났다($P < .01$). 23° 군에서는 모든 교정용 미니임플랜트가 파절이나 변형없이 인공 치근을 관통하였다.

결론

교정용 미니임플랜트가 특정 식립 각도에서 인공 치근과 접촉할 경우, 치근 관통 시에 관찰되는 MIT보다 더 낮은 수치에서 변형이나 파절이 일어날 수 있으며, 나사산 모양이 특정 삽입각도에서 파절율에 영향을 줄 수 있다. 이번 연구의 결과는 향 후 연구나 임상적 상황에 지침이 될 수 있을 것이다.

주요어 : 파절양상, 교정용 미니임플랜트, 식립각도, 나사산 형태

학번 : 2011-30680

감사의 글

본 논문을 위해 늘 부족했던 저에게 많은 지도와 격려를 해 주셨던 백승학 지도교수님, 서정훈 명예교수님, 양원식 명예교수님, 남동석 명예교수님, 장영일 명예교수님, 김태우 교수님, 이신재 교수님, 안석준 교수님, 임원희 교수님, 양일형 교수님께 진심으로 감사 드립니다. 논문심사에 힘써주신 이동렬 교수님, 허성주 교수님께도 감사 드립니다. 아울러 고려대학교 치과교정학 교실 임용규 교수님, 김예진 교수님께도 감사를 전합니다. 또한 많은 도움을 주신 대한치과교정학회 편집위원회 여러분들과 서울대학교 치과교정학 교실의 선배님들과 후배님들, 고려대학교 구로병원과 안암병원 치과교정과 선생님들에게 감사의 마음을 전합니다. 그리고 실험에 도움을 주신 Biomaterials Korea 의 임직원 여러분들께도 깊은 감사를 드립니다.

그리고, 힘든 시간을 함께해 준 제 아내와 희원이, 연성이에게도 감사의 인사를 드립니다.

2013 년 8 월

저자 씀