Original

Resonance frequency analysis of miniscrew implant stability

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Abstract: This study used resonance frequency (RF) analysis to assess miniscrew implant (MSI) stability during wound healing in a sample of 68 patients (41 women, 27 men; mean age, 27.7 years). The 104 MSIs included 66 placements in the buccal shelf (BS; 2.0 × 12 mm) and 38 placements in interradicular (IR; 1.5 × 8 mm) sites. Thirteen (12.5%) of the MSIs failed. A new RF detection device was used to measure RF at baseline (T0) and at 3 (T1), 6 (T2), 9 (T3), 12 (T4), and 15 (T5) weeks after placement. A linear mixed-effects model was fitted to change in RF values. As compared with the BS group, the IR group had significantly lower RF values on the right side from T0 through T4 and on the left side from T0 through T2. Insertion site and time of visit were significantly associated with RF value. The effects of time of visit significantly differed

between the BS and IR sites. Starting from T0, the MSIs placed at both sites had significantly lower RF values at all intervals, except for T0-T1. Future studies should examine how the present clinical protocols can optimize timing of MSI loading to maximize the success rate.

Keywords: miniscrew; implant stability; mandible; resonance frequency analysis.

Introduction

Miniscrew implants (MSIs) are established skeletal anchorage devices routinely used in orthodontic practice (1). Anchorage stability is a key factor in the success of orthodontic treatment.

Implant stability is usually divided into two stages. Primary stability results from mechanical engagement with cortical bone (implant stability reached during implant placement). Secondary stability develops from regeneration and remodeling of bone and tissue around the implant after insertion and is affected by primary stability, bone formation, and remodeling (implant stability after healing). The combined effects of primary

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Fig. 1 Implantation sites. (a) The miniscrew implant was placed in the buccal shelf. (b) The miniscrew implant was placed between the lower first premolar and the second premolar on the buccal side.

and secondary stability determine the total stability of an implant (2). After an implant placement, biological factors that affect secondary stability gradually become more important than mechanical factors that affect primary stability. Wound healing is characterized by the transition from primary mechanical stability, which is provided by local bone quality and quantity, to biological stability, which is provided by newly formed bone (3). During the healing phase, MSI stability is affected by changes caused by the remodeling processes (4).

In 2000, the Ostell device (Integration Diagnostics AB, Göteborg, Sweden) was introduced for monitoring dental implant status. When a detection device is used for resonance frequency (RF) analysis, stable coupling between the SmartPeg transducer and implant is needed. A transducer suitable for the size and structure of a particular MSI may be difficult to obtain. In addition, the head of the MSI must be modified to fit the Ostell transducer (5). For clinical use, the Implomates (BioTech One, Inc., Taipei, Taiwan) is more convenient than the Ostell for detecting RF values of MSI without modification.

This study used the Implomates, a new RF detection device, to monitor MSI stability. High and low stability were defined as high and low RF values, respectively (6), and RF measurements were used to evaluate MSI stability during wound healing.

Materials and Methods

Data from patients whose orthodontic treatment plan called for MSI insertion into the buccal shelf (BS) or interradicular (IR) sites of the mandible were analyzed

Fig. 2 Miniscrew implants. (a) Stainless steel miniscrew implant (diameter, 2.0 mm; length, 12 mm). (b) Stainless steel miniscrew implant (diameter, 1.5 mm; length, 8 mm).

(Fig. 1). Written informed consent was obtained from all patients before the study was begun. The consent procedure and treatment protocol were approved by the Institutional Review Board of Kaohsiung Medical University Hospital (KMUH-IRB-990363). This prospective study was performed in accordance with the Declaration of Helsinki guidelines for experiments involving human subjects.

The mean age of the participants (41 women, 27 men) at the insertion stage was 27.7 years (SD, 5.13 years; range, 18-37 years). After MSI placement for 3 weeks, elastomeric chains were used to apply orthodontic force (150-200 grams) to MSIs. Of the 104 stainless steel MSIs (Bio-Ray, Syntec Scientific Corp., Taipei, Taiwan) inserted, 66 were inserted at BS sites (diameter, 2 mm; length, 12 mm) as anchorage for distalization of anterior teeth and 38 were inserted at IR sites (diameter, 1.5 mm; length, 8 mm) as anchorage for mesialization of posterior teeth (Figs. 1, 2). The MSIs were self-drilling and were inserted with a hand driver.

Bisecting-angle dental radiographs and orthoradial projection technique were used for evaluation (7) and showed that MSIs for successful cases were completely separate from the root and did not touch the lamina dura or the root at implantation or after orthodontic treatment.

Resonance frequency analysis

We measured the RF of inserted MSIs at baseline (T0) and at 3 (T1), 6 (T2), 9 (T3), 12 (T4), and 15 weeks (T5) after MSI placement. All measurements were made with an RF analyzer (Implomates) (Fig. 3). Each MSI was measured three times, and the mean value was recorded.

Fig. 3 The Implomates resonance frequency analyzer used in the study. The device uses an impact force to excite resonance in the miniscrew implant. (a) The impact force is provided by a small electrically driven impact rod inside the transducer. (b) The received response signal is then transferred to a computer for frequency spectrum analysis.

Fig. 4 Resonance frequency values for the two insertion sites at five follow-up examinations separated by 3-week intervals. Whiskers indicate 95% confidence intervals. *Significant difference between groups ($P < 0.05$).

Table 1 Characteristics of the participants

Characteristic	Buccal shelf	Interradicular site
Sex		
Female	52	18
Male	14	20
Age $\pm$ SD (years)		
Right side	26.76 $\pm$ 4.58	28.34 $\pm$ 6.43
Left side	26.47 $\pm$ 4.50	28.74 $\pm$ 5.37
Side		
Total number on right side	34	21
Total number on left side	32	17
Failures on right side	2	3
Failures on left side	4	4
Visit (no. of failures)		
Visit, failure on right side	T5 (2)	T5 (3)
Visit, failure on left side	T4 (1), T5 (3)	T3 (1), T5 (3)

Table 2 Results of statistical analysis of change in resonance frequency, a linear mixed-effects model

Variable	<i>P</i> value			
Sex (male vs female)	0.33			
Age (at insertion)	0.19			
Side (right vs left)	0.49			
Site (buccal shelf vs interradicular)	0.003			
Visit (T0, T1, T2, T3, T4, T5)	<0.0001			
Test				
Site vs visit	<0.0001			

	Buccal shelf		Interradicular site	
	Adjusted mean	95% CI	Adjusted mean	95% CI
T0	11.0	10.3, 11.6	8.2	7.4, 9.0
T1	10.5	9.8, 11.1	7.6	6.8, 8.4
T2	9.0	8.4, 9.7	6.7	5.9, 7.5
T3	7.3	6.6, 8.0	5.8	5.0, 6.6
T4	6.0	5.4, 6.7	4.7	3.9, 5.5
T5	4.9	4.2, 5.6	3.7	2.9, 4.4

*Adjusted for sex, age group, and placement site status

Statistical analysis

Change in RF value at each visit was fitted to a linear mixed-effects model, which considered measurements taken at different time points and from different MSI sites in the same patient as random effects. Covariates, i.e., the fixed effects, included sex, age, insertion side (right or left), insertion site (BS or IR site), time of visit (T0-T5), and all possible interactions between visits. Adjusted mean RF values were estimated at each visit, and the difference between two insertion sites was tested for each patient. Statistical significance was defined as a P value of <0.05 . All data analysis was performed with

the SAS software package (Version 9, SAS Institute Inc., Cary, NC, USA).

Results

Of the 104 MSI placements analyzed in this study, 13 (12.5%) were failed. Table 1 shows the number of failures observed at each time point: one failure occurred at T3, one at T4, and 11 at T5.

Figure 4 shows change in RF values for the MSIs. On the right side, RF values were significantly lower in the IR group than in the BS group at T0, T1, T2, T3, and T4 (all $P < 0.05$) but did not significantly differ between

Table 3 Resonance frequency values for T0, T1, T2, T3, T4, and T5

	Buccal shelf			Interradicular site		
	Adjusted mean	95% CI	<i>P</i> value	Adjusted mean	95% CI	<i>P</i> value
T0-T1	0.46	-0.07, 0.99	0.09	0.64	0.01, 1.26	0.05
T0-T2	1.94	1.40, 2.49	<0.0001	1.47	0.83, 2.11	<0.0001
T0-T3	3.74	3.19, 4.29	<0.0001	2.28	1.63, 2.93	<0.0001
T0-T4	5.12	4.56, 5.67	<0.0001	3.42	2.78, 4.06	<0.0001
T0-T5	6.19	5.63, 6.74	<0.0001	4.43	3.80, 5.07	<0.0001
T1-T2	1.51	1.23, 1.78	<0.0001	0.82	0.47, 1.18	<0.0001
T2-T3	1.82	1.54, 2.10	<0.0001	0.81	0.45, 1.17	<0.0001
T3-T4	1.39	1.11, 1.67	<0.0001	1.13	0.77, 1.49	<0.0001
T4-T5	1.06	0.77, 1.35	<0.0001	1.02	0.63, 1.41	<0.0001

these groups at T5 ($P > 0.05$). On the left side, RF values were significantly lower in the IR group than in the BS group at T0, T1, and T2 ($P < 0.05$) but did not significantly differ at T3 through T5 ($P > 0.05$).

Table 2 shows adjusted mean RF values and 95% confidence intervals for MSIs at the BS and IR sites. Statistical analysis showed that insertion site and time of visit were significantly associated with RF value ($P = 0.003$ and $P < 0.0001$, respectively). A formal test for site-by-visit interaction suggested that the effects of the visit significantly differed between the BS and IR sites ($P < 0.0001$). RF values were not significantly affected by sex, age, or insertion side ($P > 0.05$). RF values of MSIs were significantly lower at the BS and IR sites at visits after T0 and between visits ($P < 0.0001$). The only exception was the interval T0-T1 ($P > 0.05$) (Table 3).

Discussion

Accurate measurement orthodontic MSI stability is a continuing challenge. This study compared the effects of different materials on the primary stability of MSIs by using a relatively new RF analyzer, the Implomates device, which was used in a previous study of artificial bones (8). To our knowledge, this is the first clinical study to use the Implomates to evaluate change in MSI stability during the wound healing.

RF analysis is the most promising method for noninvasive diagnostic assessment of dental implant/MSI stability. The Osstell device utilizes the basic principles of the harmonic response method. The Osstell is used by screwing the transducer into the dental implant with a torque of 10 Ncm, which is almost half the force used for implant insertion and may result in microdamage (9). The specifications and selection of transducers used for dental implants are detailed in the SmartPeg Reference Guidance (Osstell). A transducer suitable for the size and structure of a particular MSI may be difficult to obtain. In addition, the MSI head must be modified to fit the Osstell

transducer (5). When the device is used for RF analysis, stable coupling between the SmartPeg transducer and the implant is necessary. Experiments using beagles showed that failure usually occurred when the transducer was screwed into the modified head of the MSI or when it was unscrewed after recordings were obtained (10). RF analysis can also be performed by using the Implomates device for impulse force triggering. The Implomates transducer minimizes contact and avoids torque. Additionally, no installation or disassembly is required. The device uses impact force to excite resonance in the miniscrew implant. Impact force is provided by a small electrically driven rod inside the transducer (Fig. 3a). The received response signal is then transferred to a computer for frequency spectrum analysis (Fig. 3b). A dental implant study reported that Implomates RF values and implant stability quotient (ISQ) values yielded by the Osstell device exhibited a strong positive linear correlation ($r = 0.991$, $P < 0.01$) (6).

The success rate for orthodontic MSIs used as temporary anchorage range was 57% to 95.3% and usually approximated 84% (11). The present overall success rate was 87.5%. Motoyoshi et al. (12) reported MSI success rates of 88.9% to 100.0% in adults, 55.6% to 71.4% in early-load adolescents, and 90.9% to 100.0% in late-load adolescents. The titanium alloy MSIs used in their study were inserted into alveolar bones, and orthodontic forces were loaded after implant placement for 2 to 4 weeks (mean, 2.6 weeks) in early-load adolescents, for 3 months or longer (mean, 13.2 weeks) in late-load adolescents, and for 2 to 4 weeks (mean, 2.2 weeks) in adults.

Two key determinants of primary MSI stability are bone quality and quantity (13). Cortical bone quantity and quality affect long-term stability. Stationary anchorage failure is often caused by low bone density or inadequate cortical bone thickness (14). Cortical bone thickness is important in the success of an MSI because insufficient cortical bone thickness often causes inadequate primary

stability. If primary stability is not achieved at insertion, the MSI may loosen during orthodontic treatment (1,11). Motoyoshi et al. (12,15) reported that a cortical bone thickness greater than 1 mm was needed for adequate primary stability and achieved acceptable success rates for MSI placements. In most cases, altering the MSI insertion angle can compensate for insufficient cortical bone thickness.

Primary stability depends mainly on the mechanical characteristics of the original bone (its local quality and quantity), implant characteristics (geometry, diameter, length, and surface), and surgical technique used. Implant size is significantly associated with RF value. Increased insertion depth yields a high RF value, which increases primary implant stability (8). Therefore, MSI insertion depth should be maximized to obtain maximum stability. The primary stability of an MSI can also be increased by increasing implant length. Conversely, as the exposed length increases, the RF value and the primary stability decrease. In this study, the stainless steel MSIs inserted into the BS were 12 mm in length and 2 mm in diameter, whereas those inserted into the IR sites were 8 mm in length and 1.5 mm in diameter.

After MSI placement, primary mechanical stability is gradually replaced by biological secondary stability. The transition from mechanical stability to biological stability provided by newly formed bone occurs early during wound healing (3). Therefore, a critical interval in the healing process is the period during which osteoclastic activity has decreased the initial mechanical stability of the implant but new bone formation is still insufficient to maintain implant stability. Therefore, the healing period should be long enough to achieve sufficient secondary stability before loading (16).

Misch et al. (17) proposed four bone density classifications, D1-D4, based on Hounsfield units (HU): D1 for HU values greater than 1,250, D2 for HU values of 850 to 1,250 HU, D3 for HU values of 350 to 850, and D4 for HU values of 150 to 350. Dense cortical bone in the BS is classified as D1. Porous cortical bone with coarse trabeculae in the posterior mandibular IR site is D2. Thin, porous cortical bone with fine trabeculae, in some posterior mandibular IR sites, is D3. Fine trabecular bone, which is mainly found in the maxillary tuberosity, is D4. Miniscrew implant placements in D4 bone have high failure rates and are not recommended (18,19).

In this study, RF values were higher at BS sites than at IR sites. However, the differences were statistically significant only at placement and at 3, 6, 9, and 12 weeks, on the right side, and at placement and at 3 and 6 weeks, on the left side. The differences were not significant at 15

weeks, on the right side, or at 9, 12, or 15 weeks, on the left side. Both the BS and IR sites had significantly lower RF values from week 3 through week 15 (Fig. 4). Ure et al. (10) reported similar results in an animal study of MSI placements in maxillae. ISQ values decreased during the first 3 weeks after placement and increased from week 3 to week 5. At the end of the healing period, however, ISQ had not returned to the initial values.

MSIs in the mandibular BS have been proposed as a reliable source of extra-alveolar anchorage for retracting the entire mandibular arch, to correct severe crowding, protrusion, and skeletal malocclusion. Placing an MSI in an extra-alveolar site like the mandibular BS permits the use of larger-diameter screws that can be inserted parallel to the axial inclination of molars and will not interfere with tooth roots (20). Root contact during placement of miniscrews in IR sites in the alveolar process for orthodontic anchorage significantly increases the risk of implant failure (21). Even when IR placement is placement accurate, the MSI may accidentally touch an adjacent root during mesialization of posterior dentition. The proximity of an MSI to the adjacent root is an important risk factor in the failure of miniscrew anchorage. Therefore, an MSI placement that avoids root proximity is important in the stability of miniscrews for orthodontic anchorage. However, the associations of root proximity and root contact with RF values were not examined in this study, and should be investigated in future.

Bone-implant adaptation is typically measured by assessing bone-to-implant contact ratio (implant surface in contact with bone/total implant surface) (22). A bone-to-implant contact ratio as low as 5% was sufficiently resistant to orthodontic loads (16). Partial osseointegration of titanium-alloy MSIs is a distinct advantage in orthodontic applications because it provides effective anchorage and easy insertion and removal (23). Unlike titanium alloy, stainless steel bone screws tend to develop a fibrous tissue interface between the screw and bone (24). We speculate that fibrous tissues that develop around stainless steel screw threads increase risk of implant failure, by reducing the bone-to-implant contact.

Over time, differences in bone-to-implant contact can result from fibrous tissue formation caused by contact with stainless steel. Future studies should compare long-term stability of orthodontic MSIs composed of titanium alloy and those made of stainless steel. In addition, the present methods and clinical protocols should be further investigated, to determine the optimal timing of MSI loading, as indicated by skeletal anchorage success rates.

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Conflict of interest

None declared.

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