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Stable region for maxillary dental cast superimposition in adults, studied with the aid of stable miniscrews

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Structured Abstract

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Objectives – To identify a stable and reproducible reference region to superimpose serial maxillary dental models in adult extraction cases.

Setting and Sample Population – Fifteen adult volunteers were enrolled.

Methods – To reduce protrusion, bilateral maxillary first premolars were extracted in all volunteers. Each volunteer received six miniscrews, including two loaded miniscrews used to retract anterior teeth and four unloaded miniscrews. Impressions for maxillary models were taken at T1 (1 week after miniscrew placement) and T2 (17 months later). Dental models were created and then scanned using a laser scanner. Stability of the miniscrews was evaluated, and dental models were registered using stationary miniscrews. The palatal region, where deviation was within 0.5 mm in all subjects, was determined to be the stable region. Reproducibility of the new palatal region for 3D digital model superimposition was evaluated.

Results – Deviation of the medial 2/3 of the palatal region between the third rugae and the line in contact with the distal surface of the bilateral maxillary first molars was within 0.5 mm. Tooth movement of 15 subjects was measured to evaluate the validity of the new 3D superimposition method. Displacements were 8.18 ± 2.94 mm (central incisor) and 2.25 ± 0.73 mm (first molar) measured by miniscrew superimposition, while values of 7.81 ± 2.53 mm (central incisor) and 2.29 ± 1.03 mm (first molar) were measured using the 3D palatal vault regional superimposition method; no significant difference was observed.

Conclusion – The medial 2/3 of the third rugae and the regional palatal vault dorsal to it is a stable region to register 3D digital models for evaluation of orthodontic tooth movement in adult patients.

Key words: dental models; miniscrew; palate; stable region; superimposition

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Introduction

Evaluation of tooth movement depends on a stable structure. Björk (1, 2) used implants to establish a structural superimposition method for the evaluation of jaw growth and teeth displacement on a lateral head film. However, superimposition of cephalometric radiographs is subject to two types of error. The first originates from the single head film, causing difficulty in identification of landmarks, overlapping of anatomical structures, head posture changes, and magnification (3, 4). The second arises from the selection of a stable reference structure for superimposing serial head films (5). Furthermore a cephalometric radiograph is only a two-dimensional (2D) projection of a three-dimensional (3D) structure and thus cannot be used to evaluate orthodontic tooth movement in three directions.

Study casts are 3D records used to accurately document malocclusions and evaluate treatment outcome in daily orthodontic practice. In comparing serial dental models, palatal rugae are primarily used as a stable reference because medial points of the third rugae are considered to be stable throughout orthodontic treatment (6–9) unless it involves significant transverse expansion (10). Palatal rugae have historically been used to perform 2D measurements on 3D dental casts.

The development of the digital dental model increases the practicality of 3D measurement of study casts (11). Compared to plaster dental casts, digital dental models have many advantages, such as storage, retrieval, transferability, durability, communication, remote diagnosis, and treatment result evaluation. The validity and precision of digital dental models have been widely studied (12–16), and numerous studies have shown that 3D digital models can be used for model analysis (16, 17), diagnosis, and treatment planning (18, 19). However, a method for superimposing pre- and post-treatment digital models to evaluate 3D displacement of teeth is still under investigation.

To identify a stable palate region, superimposition of pre- and post-treatment digital models on various regions (20, 21) of the palatal vault were compared to traditional cephalometric superimposition to demonstrate the validity of the 3D method. A recent study (22) used anchorage miniscrews as a stable reference to detect the stable region during orthodontic treatment. Although Björk-type implants (1, 2) are thought to be stable, it has not been demonstrated whether the miniscrew remains stationary under orthodontic force. Liou et al. (23) studied the positional stability of miniscrews under orthodontic force and concluded that miniscrews are a stable anchorage method but do not remain absolutely stationary throughout orthodontic loading. EI-Beialy et al. (24) also studied the movement of miniscrews under loading and found that miniscrews were displaced in the direction of orthodontic loading.

In this study, the stability of unloaded miniscrews and anchor miniscrews was evaluated and stable screws were used as a reference to identify the relatively stable palate region for superimposing pre- and post-treatment dental models in adult extraction cases.

Materials and methods

Volunteer enrollment

Fifteen volunteers (11 men, 4 women), ranging from 21 to 41 years of age (mean 25.8 years) and characterized by maxillary protrusion, were included in this study. To reduce protrusion, bilateral maxillary first premolars were extracted in all volunteers. In each volunteer, six miniscrews were placed in the maxilla. Two miniscrews inserted into the buccal inter-radicular space between the maxillary second premolar and first molar on both sides were used for en masse retraction of anterior teeth, while four additional miniscrews were placed in other inter-radicular spaces (including the space between the maxillary second molar and first molar, canine and lateral incisors, and lateral and central incisors) and were not loaded. Four unloaded miniscrews were used for superimposition of 3D models because at least three points are required. It has also been reported that unloaded miniscrews may fail during orthodontic treatment (25). All subjects signed informed consent forms, and the research protocol was approved by the Ethics Committee of Peking University Biomedical Sciences and in accordance with the 1983 Helsinki Declaration.

Miniscrew implantation and orthodontic treatment

Titanium alloy miniscrews (Ci Bei Corporation, Zhejiang, China) used in this study were 1.6 mm in diameter and 11 mm in length (Fig. 1). Under local infiltration anesthesia, a 4-mm vertical incision was made at the mucogingival junction of the implant site. Using a screwdriver, self-drilling miniscrews were manually and directly inserted into the cortical bone. Ninety miniscrews were placed in the maxilla of volunteers, including 30 loaded and 60 unloaded miniscrews. All miniscrews exhibited good primary stability. Use of a

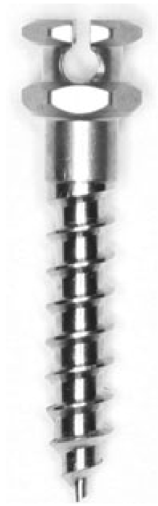

Fig. 1. Miniscrew used in this study.

2% chlorhexidine mouth rinse was prescribed for the first week after miniscrew insertion, and volunteers were instructed to maintain oral hygiene. Miniscrews remained unloaded for 1 week to allow soft tissue healing.

All patients were bonded using a 0.022-inch straight wire appliance (Xin Ya Corporation, Zhejiang, China). En masse retraction of anterior teeth was completed using a 0.019×0.025-inch stainless steel wire and a power chain with a force level between 1.5 and 2.5 N (Fig. 2). Retraction of anterior teeth against the miniscrews was stopped when the patient was satisfied with the profile or because of the molar relationship. In some cases, the extraction space was intentionally left to allow for forward movement of molars.

Maxillary digital dental model creation

Dental impressions were obtained using polysiloxane impression material (Affinis; Coltène Whaledent AG, Altstätten, Switzerland) 1 week after (T1) miniscrew placement and 17 months later (T2), when the retraction of anterior teeth by miniscrews was stopped. Dental models were generated and scanned by a 3D spot laser scanner (LPX-1200; Roland DG, Hamamatsu, Japan). The validity and precision of the scanner are both ±0.05 mm. Based on scanned data, reconstruction and analysis of 3D images were performed using reverse engineering software (Rapidform2006; INUS Technology Inc., Seoul, Korea) (Fig. 3).

Evaluation of the positional stability of the miniscrews

First, we investigated whether all unloaded miniscrews remained stable during orthodontic treatment. The distance between unloaded miniscrews was measured clockwise on maxillary digital dental models (both T1 and T2) using Rapidform2006 (Fig. 4). If the distance change between the same two unloaded miniscrews was bigger than 0.5 mm (0.5 mm was not included), it was determined that at least one of the two miniscrews

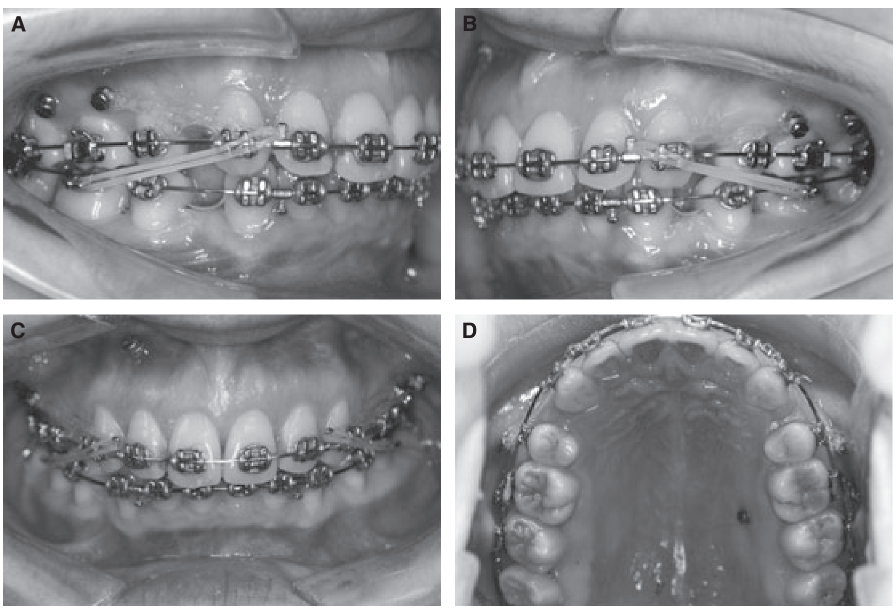

Fig. 2. En masse retraction of anterior teeth by elastic chain. Note the sites where the miniscrews were placed. A, B, C and D: Intra-oral photographs during treatment.

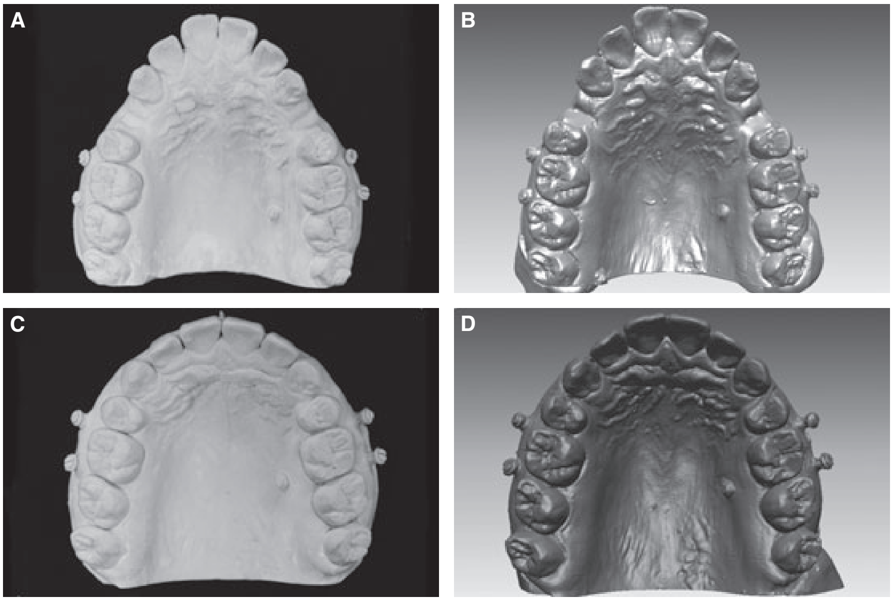

Fig. 3. (A) Maxillary plaster dental cast at T1. (B) Maxillary digital dental cast at T1. (C) Maxillary plaster dental cast at T2. (D) Maxillary digital dental cast at T2.

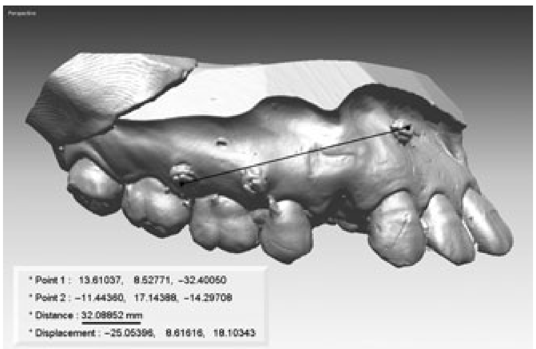

Fig. 4. Distance between two unloaded miniscrews as measured in Rapidform.

were displaced during T1 and T2, and these were marked as 'suspect miniscrews.' Next, the remaining unloaded miniscrews were used to determine which suspect miniscrews had moved. Displaced unloaded miniscrews were excluded when registering digital models of T1 and T2.

Second, we evaluated the stability of loaded miniscrews. Maxillary digital models on T1 and T2 were registered using the iterative closest point (ICP) (26) method, in which initial rotation and translation matrices are estimated using stationary unloaded miniscrews (Fig. 5). Distance changes between loaded miniscrews from T1 to T2 at each screw head were measured and compared to that of unloaded miniscrews. The difference between the positional change of loaded and unloaded miniscrews was analyzed using an independent samples *t*-test ($p < 0.01$). A loaded miniscrew was considered to be unstable when its displacement was > 0.5 mm.

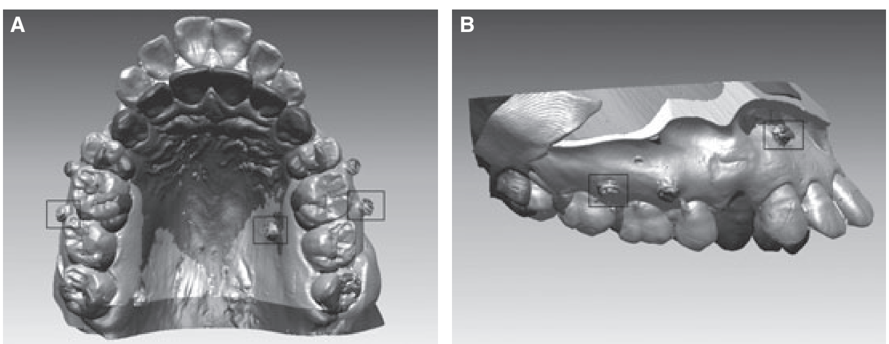

Fig. 5. Superimposition of maxillary digital casts of T1 and T2 (in gray) on stationary unloaded miniscrews. Unloaded miniscrews are indicated by rectangles. (A) Occlusal view of digital casts. (B) Lateral view of digital casts.

Establishment of a stable region for serial cast superimposition

Maxillary digital models on T1 and T2 were registered using the ICP method, in which initial rotation and translation matrices are estimated using the stationary unloaded miniscrews. This superimposition method was named the miniscrew-superimposition method. Next, the area in which deviation between the two digital dental models was ≤0.5 mm was marked in each case (Fig. 6), and the common region of the marked area of 15 subjects was extracted as the relatively stable region during orthodontic treatment. The stable region refers to the medial 2/3 of the third rugae and the following regional palatal vault (Fig. 7); 3D model superimposition performed on this region was termed the '3D palatal vault regional (PVR) superimposition.' Reproducibility of this new superimposition method refers to both validity and reliability (27).

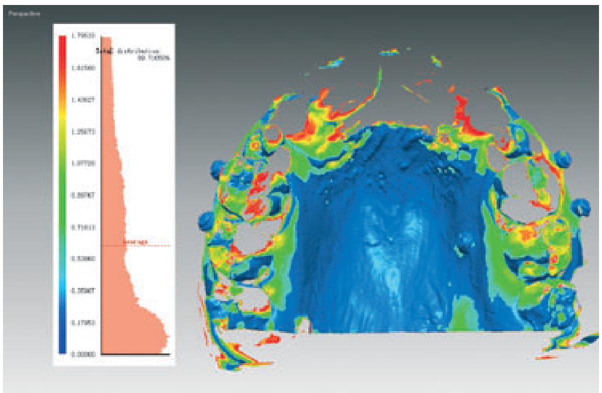

Fig. 6. The color map indicates the distance deviation of the palatal region between the two casts of one patient. The area where deviation is within 0.5 mm was selected and marked blue using Rapidform.

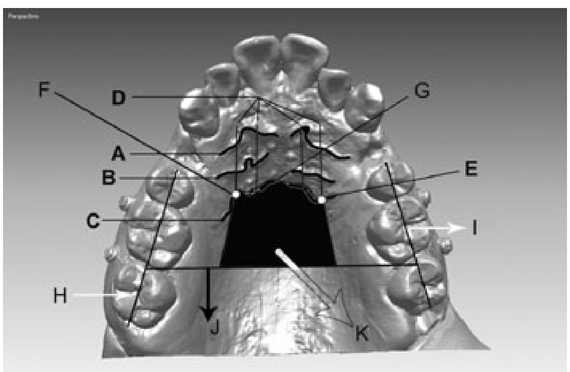

Fig. 7. (A) Right first ruga. (B) Right second ruga. (C) Right third ruga. (D) Trisection lines of the rugae. (E, F) Lateral trisection points of the left third ruga and right third ruga (G) Anterior border line of the stable palatal region. (H, I) Right and left occlusal line through the central groove of the posterior teeth. (J) Line in contact with the distal surface of the left and right maxillary first molars. (K) Stable region.

Validity of the 3D PVR superimposition method

Tooth movement in 15 subjects as measured by 3D superimposition on stationary miniscrews was used to evaluate the validity of the 3D palatal vault regional (PVR) superimposition method. Mesio-buccal cusps of the maxillary right molars and midpoints of the left central incisor edges were marked on digital models of T1 and T2. Maxillary digital models of T1 and T2 were superimposed using the miniscrew-superimposition method and the 3D PVR superimposition method, respectively. A coordinate system, modified from a previous report by Cha (20), of the pre-treatment model was created using the junction of the incisive papilla and palatine raphe as the origin (0, 0, 0), resulting in an *X*-, *Y*-, *Z*-axis and three planes (Fig. 8). Three-dimensional displacement of the maxillary right molar and left central incisor was measured, and results were analyzed using a paired T test ($p < 0.01$).

Reliability of the 3D PVR superimposition method

To evaluate the reliability of the 3D PVR superimposition method, all maxillary digital dental models on T1 and T2 were superimposed using the 3D PVR superimposition method, and displacement of the maxillary right molar and left incisor was measured by three postgraduates. The same measurement was repeated 2 weeks later by one of the postgraduates.

Result

Five of the 60 unloaded miniscrews and one of the 30 loaded miniscrews failed during the 17-month orthodontic treatment. The six failed miniscrews were observed in different subjects. The other miniscrews remained stable.

Positional stability of miniscrews

Distance changes of the two unloaded miniscrews between T1 and T2 were all <0.5 mm, and all successful

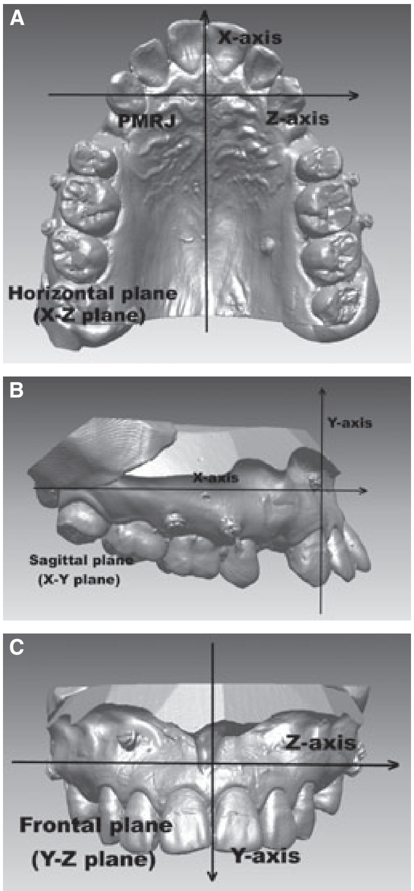

Fig. 8. Coordinate system. (A) *X–Z* horizontal plane is the section including the junction of inclusive papilla and palatine raphe (PMRJ) and parallel to the occlusal plane constructed by connecting the midpoints of the left and right central incisor edges and mesio-buccal cusp tips of the first molars using the best-fitting process. (B) *X–Y* sagittal plane is the section including one arbitrary point on the mid-palatal suture and the PMRJ and perpendicular to *X–Z* horizontal plane. (C) The *Y–Z* frontal plane is the section including the PMRJ and perpendicular to both the sagittal and the horizontal planes.

unloaded miniscrews were stationary. Displacements of loaded miniscrews were all <0.5 mm when the maxillary digital models of T1 and T2 were registered on the stationary unloaded miniscrews. Mean displacement of unloaded miniscrews was 0.23 ± 0.10 mm, while for loaded miniscrews this value was 0.24 ± 0.13 mm. No significant difference was observed between the two groups (Table 1).

Table 1. **Distance change of the miniscrew compared between unloaded and loaded miniscrews (T1–T2)**

Miniscrew type	*N*	Mean (mm)	SD	*t*	*p*-value
Unloaded miniscrew	55	0.23	0.10	–0.359	0.720
Loaded miniscrew	29	0.24	0.13		

Stable palatal region

Areas where deviation between the two digital dental models was ≤0.5 mm exhibited varying sizes and shapes in different subjects. The common region was surrounded by two transverse lines and two antero-posterior lines (Fig. 7). The anterior transverse line was a curve along the anterior outline of the third rugae, including the straight line connecting the medial points of the right and left third rugae. The posterior transverse line was in contact with left and right distal surface of the maxillary first molars. The left antero-posterior line traveled through the lateral 1/3 point of the right third ruga and parallel to the right occlusal line through the central groove of the right posterior teeth. The third ruga is a simplified line connecting the lateral and medial points when trisection is performed. The right anteroposterior line also shares these qualities. The stable palatal region is defined as the medial 2/3 of the third ruga and the regional palatal vault dorsal to it.

Validity of the 3D PVR superimposition method

Statistical description and inference of measurements using miniscrew-superimposition and 3D PVR superimposition method are shown in Table 2 (incisor displacement) and Table 3 (molar displacement). Three-dimensional displacements of the maxillary left central incisor and maxillary right first molar measured by the two methods showed no significant difference,

Table 2. **Displacement of left upper central incisor (LU1) measured according to miniscrew-superimposition (MS) and 3D PVR superimposition (3D PVRS) methods**

Variable	Mean (mm)	SD (mm)	*r*	*t*	*p*-value
LU1-MS-X	–7.32	2.53	0.995	2.964	0.010
LU1-3D PVRS-X	–7.13	2.48			
LU1-MS-Y	2.57	1.68	0.975	0.228	0.823
LU1-3D PVRS-Y	2.59	1.68			
LU1-MS-Z	0.67	2.49	0.460	0.770	0.454
LU1-3D PVRS-Z	0.24	1.00			
LU1-MS-Total	8.18	2.94	0.951	1.513	0.153
LU1-3D PVRS-Total	7.81	2.53			

X = Antero-posterior. Negative = distal movement. *Y* = Vertical. Negative = intrusion. *Z* = Buccal-lingual. Negative = lingual movement (mesio movement to upper incisor). Total = $\sqrt{(X^2 + Y^2 + Z^2)}$.

Table 3. **Displacement of right upper first molar (RU6) measured according to miniscrew-superimposition (MS) and 3D PVR superimposition (3D PVRS) methods**

Variable	Mean (mm)	SD (mm)	*r*	*t*	*p*-value
RU6-MS-X	−0.96	1.12	0.946	3.675	0.02
RU6-3D PVRS-X	−0.61	1.14			
RU6-MS-Y	−1.22	0.96	0.937	−0.349	0.732
RU6-3D PVRS-Y	−1.27	1.33			
RU6-MS-Z	−0.14	1.15	0.81	1.357	0.196
RU6-3D PVRS-Z	−0.38	1.14			
RU6-MS-Total	2.25	0.73	0.821	−0.242	0.812
RU6-3D PVRS-Total	2.29	1.03			

X = Anteroposterior. Negative = distal movement. Y = Vertical. Negative = intrusion. Z = Buccal-lingual. Negative = lingual movement (mesio movement to upper incisor). Total = $\sqrt{(X^2 + Y^2 + Z^2)}$

indicating the validity of our new 3D PVR superimposition method.

Reliability of the 3D PVR superimposition method

Interobserver reliability, which is shown by the intraclass correlation coefficient, was 0.990 (molar) and 0.999 (incisor), while the intra-observer reliability was 0.984 (molar) and 0.996 (incisor). This indicates that this 3D superimposition method is reliable.

Discussion

Björk-type implants are thought to be stable and are used as reference points to study craniofacial growth by superimposition of serial 2D lateral head films. In this study, miniscrews were used to identify a stable palatal region for registration of serial 3D maxillary digital models to evaluate tooth movement in three directions. According to a study by Julius, migration, and occasionally dislodgment, of an unloaded implant was found to cause significant errors in implant superimposition (28). We questioned whether unloaded miniscrews may also migrate during orthodontic treatment and hence would not qualify as a reference point. Several studies (23, 24) have reported that miniscrews do not remain stationary under orthodontic load. Thus, evaluation of miniscrew positional stability was needed to determine whether they can be used as reference points.

Based on our measurements, the distance change of two unloaded miniscrews from T1 to T2 were all <0.5 mm and hence could be considered as stationary. To our knowledge, the position stability of unloaded miniscrew has not been previously reported. The mean displacement of loaded miniscrews was 0.24 (±0.13) mm, which did not significantly differ from that of unloaded miniscrews. These results support a study by Wehrbein, which concluded that the palatal implant remains stationary during orthodontic treatment (29). In a study by Garfinkle et al. (25), the distance between unloaded and loaded miniscrews was measured and no significant change was observed, indicating the positional stability of loaded miniscrews. Thus, all successful miniscrews used in this study were stable enough to be used as reference points. Different results previously reported regarding the positional stability of loaded miniscrews can be attributed to several factors, including the study method, miniscrew type, implant size, implant site, orthodontic force magnitude, and the sample selected.

At least three points that are not in a straight line are required for superimposition of 3D images. In a study by Jang et al. (22), three loaded miniscrews were used as reference points to superimpose serial maxillary dental models. In our present study, four unloaded miniscrews were placed. This was performed because according to a study by Garfinkle et al. (25), the success rate of unloaded miniscrews was lower than that of loaded miniscrews (61.0 vs. 80.5%). The same result was found in our study (91.7 vs. 96.7%). Therefore, four unloaded miniscrews were placed to ensure that superimposition could be performed even if one unloaded miniscrew failed. Additionally, we found that loaded miniscrews were as stable as unloaded miniscrews. Increasing the number of stable miniscrews used in superimposition would decrease error from identification of reference points.

To decrease rotational errors during superimposition, four unloaded miniscrews were placed far from each other. We distributed reference miniscrews in the left, right, anterior, and posterior regions of the maxilla. The ability to control rotation was increased, as loaded miniscrews qualified as reference points and hence could be involved in registration. In a study by Jang et al. (22), two miniscrews were implanted on the palatal slopes between the second premolar and the first molar, and another was placed on the paramedian region of the hard palate. These insert sites have a low risk of root injury. However, the miniscrews are too close to each other and miniscrews on palatal slopes typically result in low-quality data when the models are laser scanned. The image quality of miniscrews has a strong influence on superimposition results.

By using stationary miniscrews as reference points, we could determine the area where deviation between the two digital dental models was ≤0.5 mm. The common region was extracted from 15 subjects and defined as the stable reference region. This was a continuous surface, including the medial 2/3 of the palatal vault between the third rugae and a line in contact with the distal surface of the left and right maxillary first molars.

In previous studies, several regions have been suggested as useful for superimposing maxillary digital dental models. Cha (20) superimposed pre- and post-treatment maxilla digital dental models on a surface across the palate to analyze tooth movement in extraction cases. Thiruvenkatachari (21) selected a mushroom-shaped area on the palate to superimpose pre-treatment and post-treatment casts. Both of these studies compared tooth movement measured on 3D models and demonstrated the use of 2D cephalometric measurement to validate the superimposition method. The results revealed no statistic differences between the two measurements. The superimposition region used by Cha and Thiruvenkatachari included the palatal rugae. However, displacement of the palatal rugae has been revealed in many studies. Almeida (6), Bailey (7), Van der Linden (9), and Peavy (30) reported rugae changes caused by orthodontic treatment. Simmons (31) examined anteroposterior growth changes in the palatine rugae and demonstrated that the medial rugal region anteroposterior length increased significantly.

Jang et al. used three loaded miniscrews to evaluate the stability of the palatal rugae and establish a 3D superimposition method for analyzing orthodontic tooth movement in maxillary dental models. In addition to medial points of the third rugae, they observed that the posterior region of the palatal vault was least affected by tooth movement. Thus, they defined the middle point on the line connecting medial points of the right and left third palatal rugae (Point A) and a surface 10 mm distal from the third palatal rugae (Surface B) as superimposition landmarks (22). However, in our study, we found that the region between the medial 2/3 region between the third palatal rugae and the line in contact with the distal surface of the bilateral maxillary first molars was relatively stable during treatment. This is potentially because the stable region defined by Jang excluded the 10 mm length of the palatal vault distal to the Point A, and the miniscrew placed in this region affected stability of local palatal mucosa. Soft tissue around the miniscrews is prone to irritation, which may change its shape after orthodontic treatment. Another difference is that the posterior borderline of the stable region identified in this study is more anterior than the region identified by Jang. We found that the palatal vault posterior to the line in contact with the distal surface of the bilateral maxillary first molars was not stable in two of the 15 subjects. An explanation potential reason for this is that the soft tissue covering the posterior region of the hard palate is thicker than that of the anterior region. A thicker layer of soft tissue may be deformed during impression acquisition.

The region we suggest to use for superimposition of serial maxillary dental models is located close to the middle of the palatal vault. It includes a characteristic structure – a portion of the outline of the third rugae and the area size is large enough to ensure accuracy of the superimposition. Displacements of the incisor and molar, measured using 3D PVR superimposition, were not significantly different from that measured using the miniscrew-superimposition method (Tables 2 and 3), indicating the validity of our method. The definite border of the stable region results in reliability of the new superimposition method. The high agreement of results measured by various individuals and by one person at different time points demonstrated the reliability of our superimposition method.

However, because subjects involved in this study required placement of four reference miniscrews, which were useless to patients during the phase of the experiment, the sample size was small. All subjects in this study were above 18 years old, so the shape of the palatal vault should not be affected by craniofacial growth. It remains to be shown whether 3D PVR superimposition is valid in patients whose orthodontic treatment overlaps with a growth spurt. Furthermore, it is uncertain if the method can be applied in patients who have undergone palatal expansion or a large dental expansion.

Conclusions

The medial 2/3 of the third rugae and the regional palatal vault dorsal to the third rugae are stable regions that can be used for 3D digital model superimposition to evaluate orthodontic tooth movement in adult patients in whom dental changes had occurred mainly in the sagittal dimension.

Clinical relevance

In the past, orthodontic tooth movement was primarily evaluated in two dimensions by superimposition of serial cephalometric radiographs. In this study, more than five stationary miniscrews were used to register serial maxillary dental models to find a stable and reproducible reference region during orthodontic treatment in extraction cases. A new 3D superimposition method was established to superimpose pre- and post-treatment maxillary dental models of adult patients and to demonstrate that 3D changes in all teeth can be accurately presented and measured.

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