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Maxillary cortical bone remodeling characteristics in extraction patients: A cone-beam computed tomography study

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Introduction: This study aimed to evaluate labial and palatal cortical bone remodeling (BR) characteristics and related aspects of maxillary incisors after retraction, as these aspects are still controversial among orthodontists. **Methods:** Cortical BR and incisor movement of 44 patients (aged 26.18 ± 4.71 years) who underwent maxillary first premolar extraction and incisor retraction were analyzed using superimposed cone-beam computed tomography images. Labial BR/tooth movement (BT) ratios at the crestal, midroot (S2), and apical (S3) levels were compared using the Friedman test and pairwise comparisons. Multivariate linear regressions were used to explore the relationships between the labial BT ratio and several factors, including age, ANB angle, mandibular plane angle, and incisor movement patterns. According to the type of palatal cortical BR observed, the patients were divided into 3 groups: type I (no BR without root penetration of the original palatal border [RPB]), type II (BR with RPB), and type III (no BR with RPB). Student's *t* test was used to compare the type II and III groups. **Results:** The mean labial BT ratios at all levels were <1.00 (0.68-0.89). This value at the S3 level was significantly smaller than that at the crestal and S2 levels ($P < 0.01$). Multivariate linear regression indicated that the tooth movement pattern negatively correlates with the BT ratio at S2 and S3 levels ($P < 0.01$). Type I was noted in 40.9% of the patients, and similar proportions exhibited type II (29.5%, 25.0%) or type III remodeling (29.5%, 34.1%). The retraction distance of the incisors in type III patients was significantly larger than in type II patients ($P < 0.05$). **Conclusions:** The amount of cortical BR secondary to maxillary incisor retraction is less than the tooth movement. Bodily retraction may lead to lower labial BT ratios at the S3 and S2 levels. Roots penetrating the original border of the cortical plate are necessary for palatal cortical BR initiation. (Am J Orthod Dentofacial Orthop 2023;164:160-71)

Most patients with maxillary or bimaxillary protrusion seek orthodontic treatment to improve their convex profile.[1,2] Camouflage treatment strategies include premolar extraction and a certain amount of palatal incisor movement. Torque control is often applied to prevent undesirable palatal inclination of maxillary incisors during long-distance movement. Orthodontists believe that controlled retraction of the maxillary incisors could result in backward movement of both skeletal and soft-tissue A points,[2-4] which would help achieve a better profile and harmonious lip relationship.[5] However, excessive torque control may lead to root resorption[6,7] or palatal bony defects.[8] Thus, the balance between risk and return is crucial. Several studies have discussed tooth movement (TM) strategies[9] for the retraction of maxillary incisors. However, alveolar bone remodeling (BR) ability and its proportional relationship with TM remain controversial.[10,11] There is a long-standing controversy regarding whether teeth move with the bone[12,13] or through the bone.[14] With the development of cone-beam computed tomography (CBCT), orthodontists have gradually established a method of measuring the labial-lingual alveolar bone thickness in longitudinal sections of incisors.[15-17] A limitation of this method is that the positions of both the incisor and the alveolar bone change during orthodontic treatment. Measurements based on an

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inconsistent reference system cannot accurately assess changes in the surrounding tissue. Some researchers have noted the shortcomings of the existing methods and used stable structures as references. Eksriwong and Thongudomporn[11] used the palatal plane as a stable reference to overcoming this shortcoming and concluded that the changes in the labial alveolar bone followed the TM at an almost 1:1 BR/TM (BT) ratio and the palatal alveolar bone was stable. In recent years, the CBCT superimposition technique based on voxel-based registration has proven accurate and stable.[18-20] Moreover, this technique has helped orthodontists research treatment outcomes, such as midpalatal suture expansion,[21,22] TM,[23,24] periodontal change,[25] and orthognathic treatment.[26]

This study aimed to explore the labial and palatal cortical BR characteristics of retracted maxillary incisors. The extent of cortical BR and TM was measured at different root levels using CBCT superimposition based on voxel-based registration.

MATERIAL AND METHODS

This retrospective study was approved by the Institutional Review Board at Peking University Hospital of Stomatology (approval no. PKUSSIRB-201631110). Based on the 10 subjects per variable rule,[27-29] the minimum sample size of this study was 40. Finally, 44 adult patients (aged 26.18 ± 4.71 years; 40 females, 4 males; treatment time, 37.47 ± 9.62 months) were selected from an orthodontic practice group and a database of 2000 patients in the Department of Orthodontics, Peking University School and Hospital of Stomatology. The inclusion criteria were (1) the removal of bilateral maxillary first premolars during the orthodontic treatment with the edge of maxillary incisors retracted >4 mm without obvious intrusion; (2) crowding in the maxillary arch <2 mm; (3) no evidence of periodontal or gingival problems at the beginning of orthodontic treatment; (4) no history of trauma to the maxillary and mandibular anterior teeth; (5) good general and oral health and no use of anti-inflammatory drugs for at least 6 months before or during orthodontic treatment; (6) treatment with 0.022-in MBT brackets, leveled and aligned with nickel-titanium, 0.019 × 0.025-in stainless steel archwires for space closing, all anterior teeth (canine-to-canine) were retracted en-masse with the use of sliding mechanics; and (7) pretreatment (T0) and posttreatment (T1) CBCT scans obtained using a NewTom VG scanner (Aperio Services, Verona, Italy) with the scanning parameters of 15 × 15 cm field of view, 110 kVp, 1-3 mA, 10-second scan time, and 0.3-mm voxel size. The exclusion criteria were (1) root length (the distance from the cementoenamel junction to apex) of maxillary incisors was <9 mm in T1 CBCT; and (2) low CBCT image quality, the cortical bone and root could not be defined accurately. Landmarks on the cortical bone, the labial and palatal border of the alveolar bone, were chosen to represent the change in the alveolar bone in this study.

Because the institution adopts standard electronic medical records, each medical record recording format and method were consistent.

CBCT data process was shown in Figure 1. In the Dolphin Imaging 3D program (version 11.9; Dolphin Imaging and Management Solutions, Chatsworth, Calif), the head position of T1 CBCT was adjusted as follows: the plane determined by sella (S), nasion (N), and basion (B) was the midsagittal plane, and the palatal plane determined by the anterior nasal spine (ANS)-posterior nasal spine (PNS) was the axial plane.

CBCT scans of T0 and T1 were superimposed with voxel-based registration, consistent with the anterior cranial base[30-32] (Figs 2, *A-C*). In the superimposed axial section, the sagittal slice location line was adjusted until it passed through the root centers of the incisors on T0 and T1 scans (Figs 2, *D* and *E*). T0 and T1 sagittal slices were subsequently exported separately with a scale ruler (Figs 2, *F* and *G*).

The T0 and T1 CBCT scans were opened in Procreate (version 4.3; Savage Interactive, Hobart, Tasmania, Australia), and the slices (T0) were used to outline the buccolingual border of the alveolar bone and incisor edge. The sketch and slice (T1) were merged into 1 superimposed image, and the crestal (S1), midroot (S2), and apical (S3) level reference lines were marked and saved in jpeg format (Fig 3).

The measurements were performed using ImageJ (version 1.48; National Institutes of Health and the Laboratory for Optical and Computational Instrumentation, University of Wisconsin, Madison, Wis). To measure the position changes in the labial and palatal root and alveolar bone in superimposed images, each tooth was measured at S1, S2, and S3 levels from the cementoenamel junction every 3 mm along the axis of the incisor. The scale was set before measurement. The following measurements were obtained (1) alveolar BR, which is the horizontal distance between labial or palatal alveolar bone on T0 and T1 scans; (2) TM, defined as the horizontal distance between the labial or palatal borders of the incisor root on T0 and T1 scans; (3) the BT ratio, defined as BR divided by TM; and (4) incisor movement pattern (IMP) representing the retraction type of incisors, which is defined as TM (S3)/TM (S1). The larger the IMP value, the more the incisors

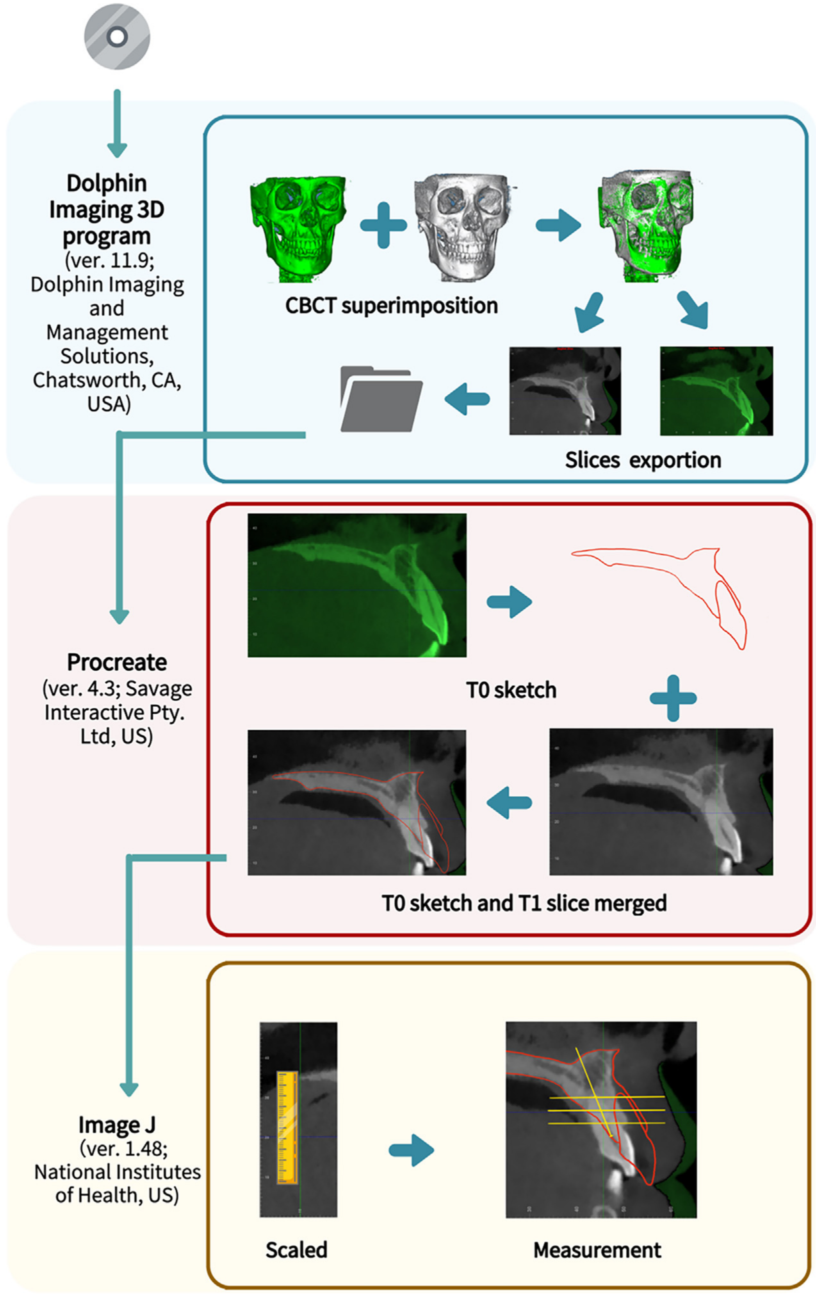

Fig 1. Data processing flow chart.

exhibited bodily retraction. In contrast, smaller IMP values indicated incisor tipping (Fig 4).

To demonstrate the features of palatal BR more clearly, all patients were classified according to whether the root penetrated the original cortical bone border and whether BR was detected (Fig 5). Classifications were (1) type I: no palatal BR without root penetration of the original palatal border, (2) type II: palatal BR with root penetrating the original palatal border, and (3) type III: no palatal BR with root penetration of the original palatal border.

Type III patients were not included in calculating the mean value of palatal measurement items because of the defect of the alveolar bone on the palatal side.

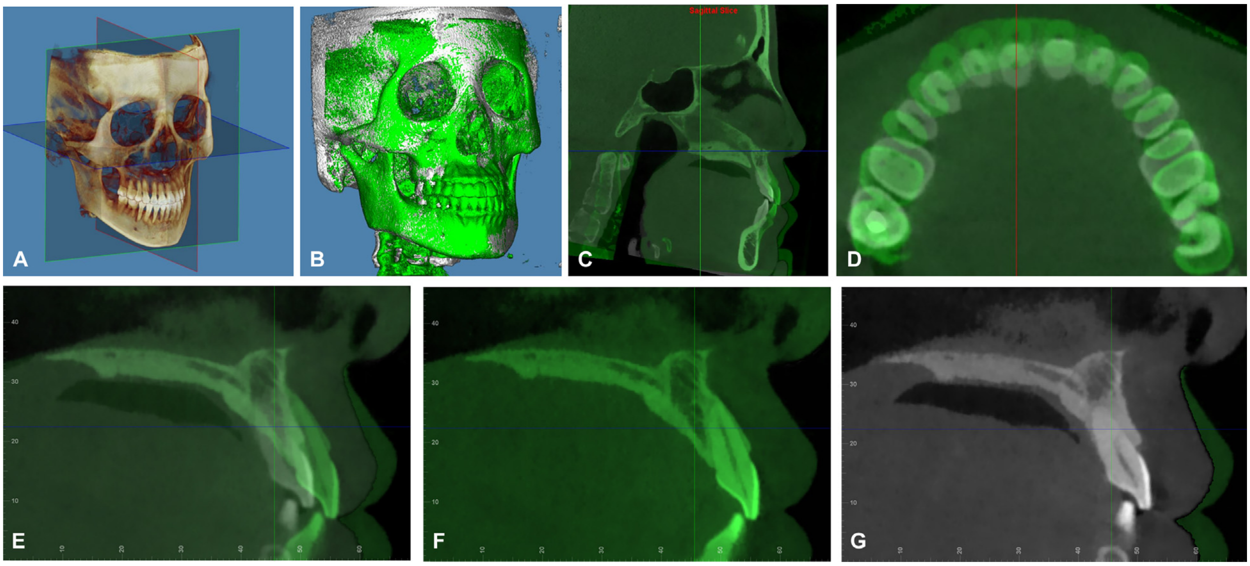

Fig 2. CBCT data processing in Dolphin Imaging software: **A,** Head position; **B,** T0 (*green*) and T1 (*white*) CBCT scans superimposition results, consistent with the anterior cranial base; **C,** Palatal plane (ANS-PNS) was the axial plane; **D,** Red indicates the sagittal slice passing through the cross-section for center points of T0 and T1 incisors; **E,** Superimposed sagittal slice; **F,** T0 sagittal slice; **G,** T1 sagittal slice.

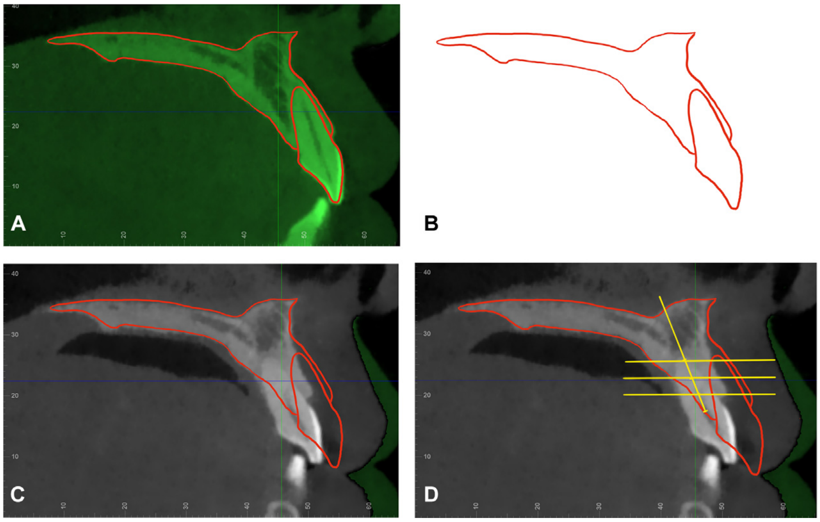

Fig 3. CBCT data processing in Procreate: **A,** T0 sagittal slice; **B,** Pretreatment T0 sketch; **C,** T0 sketch and T1 sagittal slice merged image. **D,** S1, S2, and S3 level reference lines (*yellow*).

Statistical analysis

All measurements were performed by 1 investigator (S.W.), who performed repeated measurements for 25 randomly selected CBCT scans with an interval of 2 weeks. Interexaminer calibration was performed by another investigator (R.G.), who also measured these 25 samples twice with an interval of 2 weeks.

Statistical analysis was performed using SPSS software (version 21.0; IBM, Armonk, NY). Method reliability was evaluated using intraclass correlation coefficients (ICCs) computed with a 2-way random model and absolute agreement. Measurement error was evaluated using the method of moments estimator (MME) formula.[33]

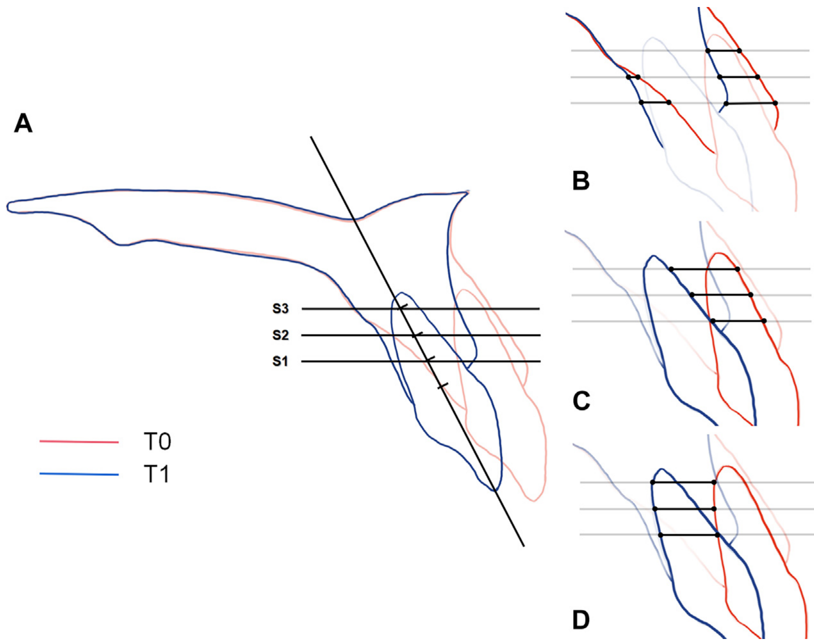

Fig 4. Measurement items: **A,** S1, S2, and S3 levels of maxillary incisors; **B,** Labial and palatal alveolar BR; **C,** Labial TM; **D,** Palatal TM.

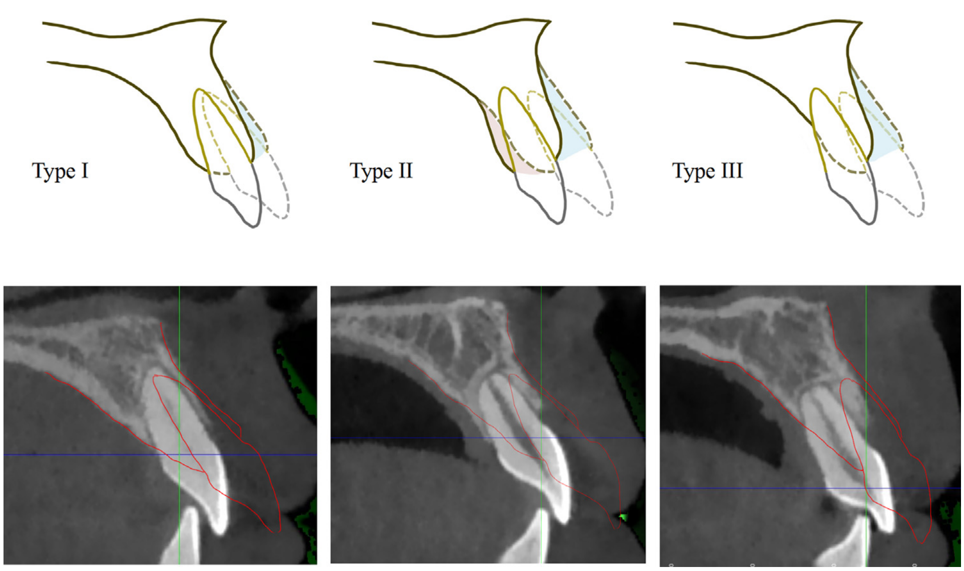

Fig 5. Different types of BR on palatal cortical bone. *Blue*, labial BR; *Red*, palatal BR; *Dashes*, original cortical bone and incisor; *Line*, cortical bone and incisor after retraction.

The Shapiro-Wilk test results showed that the data were normally distributed. However, the variance in labial BT ratios was not uniform, and Friedman's test and pairwise comparisons were used to evaluate the labial BT ratio difference among the S1-S3 levels.

Multiple linear regression was used to explore the relationship between labial cortical BR and possible related factors. T11 (maxillary right incisor) and T21 (maxillary left incisor) BT ratio at all 3 levels were chosen as dependent variables. The independent variables were:

Table I. ICC and MME error of repeated measurements

	Palatal				Labial			
	TM		*BR*		*TM*		*BR*	
Levels	*ICC*	*MME error*	*ICCs*	*MME error*	*ICCs*	*MME error*	*ICC*	*MME error*
Examiner 1								
S1	0.972	0.28	0.959	0.14	0.97	0.27	0.964	0.22
S2	0.976	0.27	–	0	0.986	0.21	0.961	0.22
S3	0.985	0.23	–	0	0.985	0.27	0.956	0.2
Examiner 2								
S1	0.983	0.23	0.994	0.06	0.971	0.2	0.915	0.4
S2	0.989	0.19	–	0	0.984	0.21	0.953	0.24
S3	0.986	0.23	–	0	0.987	0.28	0.951	0.19
Examiner 1-examiner 2								
S1	0.961	0.33	0.829	0.27	0.969	0.25	0.942	0.28
S2	0.95	0.41	–	0	0.986	0.19	0.94	0.27
S3	0.945	0.44	–	0	0.981	0.29	0.932	0.23

ICC, intraclass correlation coefficients; *MME*, method of moments estimator; *TM*, tooth movement; *BR*, bone remodeling.

age, ANB angle, mandibular plane angle (Mp-SN), and T11 or T21 IMPs. The histogram of residuals and the scatter diagram of dependent variables and standardized residuals were used to investigate the normality and homogeneity of variance in the 6 regression models.

The differences in possible related factors (age, ANB angle, Mp-SN, IMP and TM [S1]) between patients with type II and type III palatal BR were verified using independent sample *t* tests. The significance of all tests was established at $P < 0.05$.

RESULTS

For examiner 1, the intraexaminer ICCs ranged between 0.956 and 0.986, and the MME error ranged from 0.14 to 0.28 mm. For examiner 2, the intraexaminer ICCs ranged between 0.915 and 0.989, and the MME error ranged from 0.06 to 0.28 mm. Both examiners demonstrated good self-stability. The interexaminer ICCs ranged between 0.829 and 0.986, and the MME error ranged from 0.19 to 0.44 mm (Table I).

The average ANB angle was 4.58° ± 2.23° and the Mp-SN was 38.07° ± 5.78° at T0. TM at the S1 level was 3.63 ± 1.18 mm (T11) and 3.54 ± 1.10 mm (T21), showing that the incisor crowns retracted a certain distance in the samples. The TM at the S3 level was 2.05 ± 1.63 mm (T11) and 2.12 ± 1.65 mm (T21), and the IMP was 0.53 ± 0.29 (T11) and 0.56 ± 0.30 (T21) (Table II). The IMP is determined by TM (S3)/TM (S1). The closer the IMP value is to 0, the more the incisors tend to show tipping; the closer the IMP value is to 1, the more the incisors tend to show bodily retraction. These results demonstrated that IMPs varied from tipping to bodily retraction in this study.

The mean BT ratios at the S1-S3 levels were all <1, and the differences among these 3 levels are shown in the box diagram (Table II; Fig 6). Friedman's test revealed significant differences among BT ratios at levels S1-S3 ($P < 0.05$). The pairwise comparison demonstrated that the BT ratios at the S1 and S2 levels were not significantly different, but both of them were significantly larger than the BT ratio at the S3 level ($P < 0.01$) (Table III).

Multivariate linear regression models demonstrated that the TM pattern has a negative relationship with the BT ratio (S2) and (S3) (Fig 7), but has no significant relationship with the BT ratio (S1). However, age, ANB angle, and Mp-SN exhibited no significant influence on BT ratios at all 3 levels (Table IV).

Most roots penetrated the original bone border, and the proportions of types II and III patients were similar (Table V). The mean value of palatal measurement items of type I and II patients was shown in Table VI. The retraction distance of the incisors in type III patients was significantly greater than in type II patients. However, these patients had no significant differences in age, ANB, Mp-SN, and IMP (Table VII).

DISCUSSION

Alveolar BR with TM is the foundation of orthodontic treatment. The classic theory, which states that alveolar bone resorption occurs on the pressure side and bone apposition on the tension side, may explain why moving teeth remain stable in the bone. However, this theory cannot satisfactorily explain the absence of an increase in the thickness of the labial alveolar bone by the same amount of TM when a maxillary incisor is retracted. In

Table II. Mean and standard deviation of measurement items on the labial side of the cortical bone

Levels	*TM (mm)*	*BR (mm)*	*BT ratio*	*IMP*
T11 (n = 44)				
S1	3.63 ± 1.18	3.21 ± 1.06	0.89 ± 0.15	
S2	2.85 ± 1.42	2.29 ± 0.97	0.85 ± 0.22	0.53 ± 0.29
S3	2.05 ± 1.63	1.29 ± 0.87	0.74 ± 0.41	
T21 (n = 44)				
S1	3.54 ± 1.10	3.10 ± 0.99	0.88 ± 0.14	
S2	2.80 ± 1.34	2.22 ± 0.92	0.82 ± 0.21	0.56 ± 0.30
S3	2.12 ± 1.65	1.23 ± 0.80	0.68 ± 0.37	

Note. Values are shown as mean ± standard deviation.
TM, tooth movement; *BR*, bone remodeling; *BT*, BR/TM; *IMP*, incisor movement pattern.

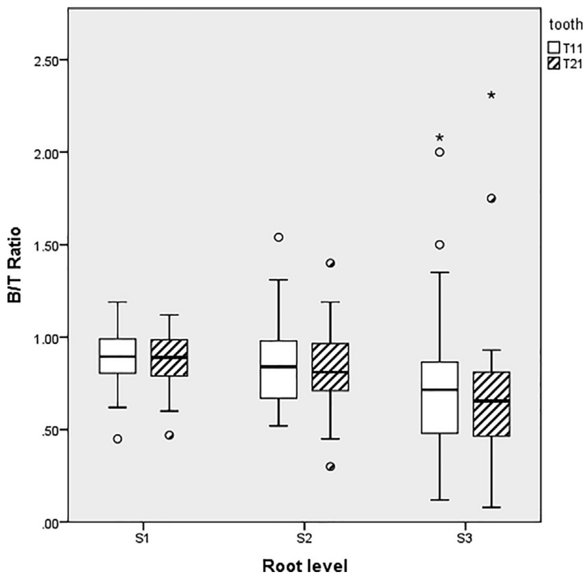

Fig 6. BT ratios at different levels on the labial side of maxillary incisors. *BT*, bone remodeling/tooth movement.

Table III. Pairwise comparison results between BT ratios at different levels on the labial side of maxillary incisors

Levels	P *values*
T11 BT ratio	
S1-S2	1.000
S2-S3	0.001*
S1-S3	<0.001**
T21 BT ratio	
S1-S2	0.548
S2-S3	<0.000**
S1-S3	<0.000**

BT, bone remodeling/tooth movement.
**P* <0.01; ***P*<0.001.

this study, CBCT data before and after treatment were superimposed with voxel-based CBCT registration, consistent with the anterior cranial base. The TM and alveolar BR values could be directly measured on the superimposed images. We used this new method to demonstrate that cortical bone exhibits a complex remodeling pattern when the incisor position changes. Bone changes occurred around periodontal ligaments and on the surface of cortical bone. Moreover, the cortical BR pattern differs from the alveolar bone around the periodontal ligament. This study investigated the labial and palatal cortical BR, its relationship with TM, and other potentially related factors.

In this study, the central incisors were chosen to represent the characteristics of cortical BR in the incisor region of the maxillary alveolar process. The experimental method in this study focused on simultaneously quantifying TM and BR. In the lateral incisor region, measurement discrepancies in the direction in which a tooth moves and the actual cortical bone corresponding to the roots can affect BR and TM assessment. Therefore, the central incisors are considered the most representative teeth because they retract in the same direction as the bone remodels. In previous studies, the lateral incisors demonstrated BR characteristics similar to those of the central incisors. Thus, we selected the central incisors as the representative incisors.

The cortical bone shows different remodeling characteristics at different sites. The labial cortical bone shows obvious changes with the retraction of maxillary incisors. The data and box diagrams showed that the mean BT ratios at all 3 levels were <1 (Fig 6; Table II), indicating that the remodeling of the labial alveolar bone was less than the amount of TM when the incisor was retracted, which was bound to cause bone thickening on the labial side of incisor roots.[34] Our data showed that the BT ratios were inconsistent at different root levels. The BT ratio at the S3 level was significantly lower than that at the S1 and S2 levels (Fig 6; Table III), indicating that the

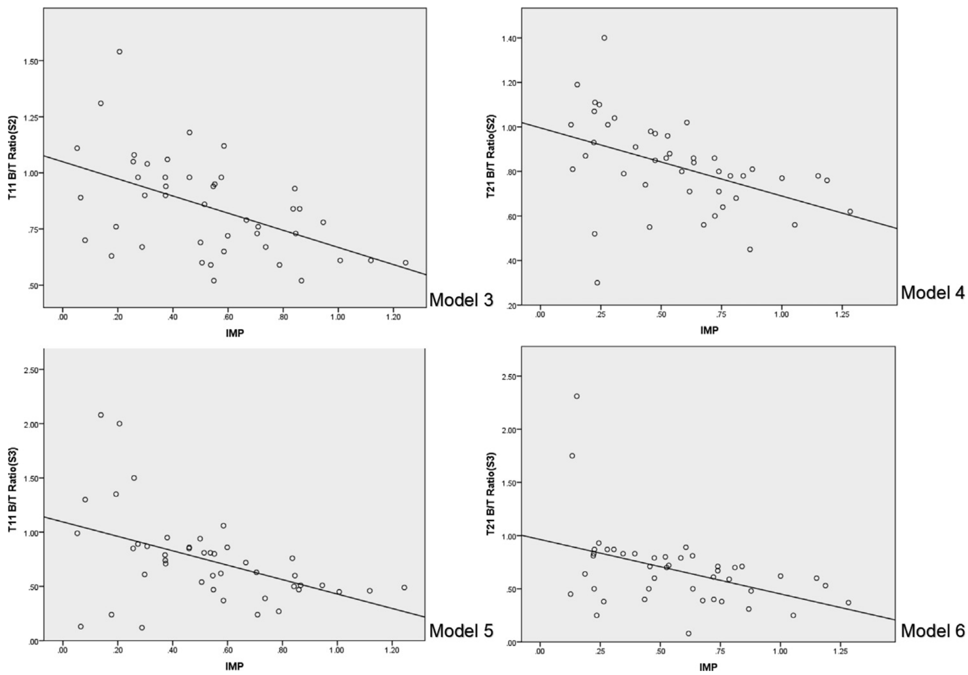

Fig 7. Scatter plots from models 3 to 6.

Table IV. Linear regression from models 1 to 6

			Independent variable								
			AGE		*ANB*		*Mp-SN*		*IMP*		
Model	*Dependent variable*	*Constant*	*β*	P *value*	*β*	P *value*	*β*	P *value*	*β*	P *value*	r^2
	BT ratio (S1)										
1	T11	0.915	0.001	0.763	−0.018	0.116	0.002	0.637	−0.106	0.202	0.123
2	T21	0.905	−0.002	0.775	−0.004	0.739	0	0.914	0.023	0.782	0.005
	BT ratio (S2)										
3	T11	1.201	−0.006	0.374	−0.024	0.117	0.002	0.716	−0.322	0.005*	0.312
4	T21	0.914	0	0.971	−0.008	0.603	0.003	0.622	−0.302	0.009*	0.208
	BT ratio (S3)										
5	T11	0.506	0.019	0.139	0.022	0.455	0.001	0.904	−0.78	0.001*	0.27
6	T21	1.022	0.004	0.762	0.033	0.218	−0.007	0.477	−0.568	0.005*	0.213

BT, bone remodeling/tooth movement; *IMP*, incisor movement pattern.
*P <0.01.

Table V. Classification of BR patterns at different levels on the palatal side of maxillary incisors

	BR patterns		
Tooth	*Type I*	*Type II*	*Type III*
T11	18 (40.9%)	13 (29.5%)	13 (29.5%)
T21	18 (40.9%)	11 (25.0%)	15 (34.1%)

Note. Values are shown as n (%).
BR, bone remodeling.

alveolar bone at the S3 level was less affected by TM; in contrast, BR was more active in the alveolar ridge crest region. This result was consistent with that of Ahn et al,[25] who observed that the thickness of labial alveolar bone at the middle level showed a larger increase than that at the cervical level. Zhang et al[35] found that the thickening trend of alveolar bone was more evident closer to the root tip.

To further explore the effect of the incisor movement pattern on the labial BT ratio, we introduced the

Table VI. Mean and standard deviation of measurement items on palatal side of cortical bone (types I and II)

Levels	*TM (mm)*	*BR (mm)*	*IMP*
T11			
S1	3.27 ± 1.21	0.36 ± 0.60	0.59 ± 0.26
S2	2.68 ± 1.33	0.12 ± 0.49	
S3	2.15 ± 1.49	0.00 ± 0.04	
T21			
S1	3.34 ± 1.15	0.26 ± 0.53	0.65 ± 0.26
S2	2.84 ± 1.32	0.08 ± 0.35	
S3	2.33 ± 1.48	0.00 ± 0.01	

Note. Values are shown as mean ± standard deviation.
TM, tooth movement; *BR*, bone remodeling; *IMP*, incisor movement pattern.

Table VII. Independent sample t test of relevant factors between type II and III patients

Factors	*Type II*	*Type III*	*t value*	P *value*
T11				
n	13	13		
Age (y)	27.00 ± 5.52	26.54 ± 3.65	0.252	0.804
ANB (°)	3.99 ± 1.65	5.75 ± 2.61	−2.028	0.054
Mp-SN (°)	38.50 ± 5.77	40.08 ± 7.15	−0.631	0.534
IMP	0.70 ± 0.21	0.70 ± 0.21	−0.356	0.725
TM (S1) (mm)	3.73 ± 1.23	4.92 ± 1.04	0.274	0.013*
T21				
n	11	15		
AGE	25.54 ± 5.57	27.47 ± 3.94	−1.03	0.313
ANB (°)	4.75 ± 1.99	5.32 ± 2.68	−0.579	0.568
Mp-SN (°)	39.09 ± 5.28	39.57 ± 7.18	−0.188	0.852
IMP	0.62 ± 0.27	0.71 ± 0.25	−0.815	0.423
TM (S1) (mm)	3.34 ± 1.11	4.32 ± 1.24	−2.070	0.049*

Note. Values are shown as mean ± standard deviation.
IMP, incisor movement pattern; *TM*, tooth movement.
*$P < 0.05$.

IMP value. IMP was the TM ratio between root S3 and S1 levels. According to the multivariate linear regression results, the movement pattern of the incisor was significantly correlated with the BT ratio at the middle and S3 levels (Table IV). The more the tooth showed bodily retraction, the smaller the BT ratio was at these 2 levels. According to the β values, the BT ratio at the S3 level was more affected by IMP than at the S2 level. The influence of the TM pattern on the labial alveolar bone gradually decreased from the cervical level to the S3 level. The BT ratio at the S3 level can be as low as 0.3-0.4 when the IMP is high. This shows that a backward S3 movement of the root by 1 mm can only provide some patients with 0.3-0.4 mm remodeling of the cortical bone in the corresponding region. Notably, torque control is one major factor related to root resorption.[6,7] In patients with thinner palatal alveolar bones, such as hyperdivergent skeletal Class II patients, excessive torque-controlled retraction of maxillary incisors may lead to obvious palatal bone fenestration or dehiscence. Depending on individual patient characteristics, the orthodontist should consider the risk of high torque control movement for very limited BR in the S3 area and carefully weigh the pros and cons of excessive torque control.

If only the average labial BT ratio value were calculated, the movement pattern of incisors in selected patients would significantly affect the conclusion of the study. In the CBCT study by Eksriwong and Thongudomporn,[11] the sample consisted mainly of tipping incisors, resulting in larger BT ratios than our study. A similar result was also observed in a cephalometric study by Vardimon et al,[10] in which the BT ratio of the tipping incisor was slightly higher than that by torque control retraction.

This study conducted a multiple linear regression analysis on the possible factors related to the labial BT ratio. IMP shows a negative relationship with the BT ratio at S2 and S3 levels (Table IV). Consistent with previous research results, TM patterns, such as changes in inclination, were found to be related to alveolar bone thickness during maxillary incisor retraction.[10] Although high-angle patients may have thinner cortical bones,[36,37] no relationship was detected between Mp-SN values and BT ratios. Because the patients included in this study were all young adults, age showed no statistically significant regression outcomes. The r^2 of models 3-6 were 0.208-0.312, indicating that other factors must be related to alveolar BR, except for the TM pattern.

Compared with the labial side, palatal BR shows completely different characteristics. There was a continuous correlation between labial cortical BR and root movement; once roots moved palatal, BR started simultaneously. However, different types of BR were observed on the palatal side in our sample (Table V). We propose a new classification method to identify each situation. The amount of alveolar bone decreased in types I or II, but the bony periodontal wrapping of the root was maintained. Bone fenestration or dehiscence was identified in type III. When the root moved beyond the original border of the palatal cortical bone, the rates of types II and III were similar. Approximately one-third of the patients with incisor retraction was in the type III group.

It should be noted that both the thickness and height may reduce in the palatal alveolar bone of these patients after orthodontic treatment. It is the ideal condition in orthodontic treatment when teeth retract, BR occurs simultaneously on the labial and palatal sides, and the amount of alveolar bone is maintained. However, no site of this type was detected in our sample. The root-penetrated cortical plate may act as a trigger point in initiating palatal cortical BR. Previous studies have reported that the cortical plate is a critical border in palatal BR.[11,38,39] Because of this trigger condition, the extent of alveolar BR on the palatal side was significantly lower than on the labial side (Tables II and VI).

The amount of incisor retraction was significantly greater in type III patients than in type II patients. There was no statistically significant difference in the TM pattern between patients in these 2 groups (Table VII). These findings suggest that excessive TM with either bodily retraction or tipping should be avoided as it increases the risk of palatal bone defects.

Because of the defect of alveolar bone in some parts of the palatal side in type III patients, it was impossible to measure the value of BR accurately. Therefore, we excluded data from type III patients when calculating the mean value of palatal measurement items. Although this operation may have led to an underestimation of the effectiveness of palatal BR, the amount of palatal remodeling is much smaller than that of labial remodeling, and the gap between the 2 types of remodeling was substantial. Therefore, it was considered that this underestimation had little effect on the difference between the 2 types of remodeling (Table VI). Concurrently, it should be noted that the spatial resolution of the CBCT images was not determined using a phantom as recommended for buccal bone measurements[40,41] and, therefore, not known in this study. It means the thin alveolar bone covering the roots on the palatal aspect may not be visualized on CBCT images.[42] The specificity of CBCT in detecting fenestrations ranged from 0.77 to 0.81, whereas the sensitivity ranged from 0.71 to 0.81. In addition, the specificity in detecting dehiscence ranged from 0.73 to 0.95, whereas the sensitivity ranged from 0.42 to 0.83.[43,44] This may also result in an underestimation of palatal alveolar BR ability.

As a retrospective CBCT study, this study quantitatively analyzed the TM and alveolar BR before and after treatment; however, it could not identify the BR at a specific time point in the complex TM of orthodontic treatment. The important influence of biomechanical factors on alveolar BR should not be ignored. Continuous light force can stimulate alveolar BR more effectively than heavy force. Different mechanical or appliance systems may also stimulate different types of BR. These need to be further explored in prospective clinical research with a larger sample under precisely controlled conditions.

The maxillary process acts as a functional complex; when the tooth position changes, alveolar BR occurs to adjust and support its new functional condition. The results of this study emphasize the need to consider the varying alveolar BR ability at different sites of the maxillary incisor region and improve the profile of the patients while ensuring tooth health.

CONCLUSIONS

1. Labial and palatal alveolar bone has different remodeling characteristics. The labial alveolar bone maintains a continuous remodeling pattern with TM once the tooth is retracted, whereas the palatal

alveolar bone shows different remodeling patterns among patients.
2. The remodeling of the labial alveolar bone is less than the TM amount at all levels after maxillary incisor retraction. The maxillary labial alveolar BR ability gradually decreases from the S1 to the S3 level. The alveolar bone at the S3 level is less affected by TM.
3. The TM pattern affects labial alveolar BR at the S3 and S2 levels. Bodily retraction may lead to less BR than the amount of TM at these 2 levels.
4. A new classification method was developed to identify different palatal alveolar BR situations according to the relationship between incisor root and original palatal border and BR.
5. The penetration of the roots in the original border of the cortical plate is necessary for palatal BR initiation.
6. The greater the retraction of the maxillary incisors, the higher the probability of bone fenestration occurring on the palatal side.

AUTHOR CREDIT STATEMENT

Shuo Wang contributed to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, original draft preparation, manuscript review and editing, and visualization; Dawei Liu contributed to manuscript review and editing; Runzhi Guo contributed to resources and investigation; Yiping Huang contributed to manuscript review and editing; Xiaomo Liu contributed to resources and investigation; Xuedong Wang contributed to resources and investigation; Weiran Li contributed to supervision and project administration.

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