Original Article

Effect of the Proximity of Roots to the Cortical Plate and Inclination of Incisors on External Apical Root Resorption

Abstract

Background: External apical root resorption (EARR) is an unfavorable side effect of orthodontic treatment. Orthodontic treatment of patients with increased crowding could lead to the proclination of incisors and proximity of roots to the cortical plates. **Aims:** The aim of this study was to evaluate the effects of the proximity of the labial and lingual cortical plates and the inclination of incisors on EARR. **Settings and Design:** Twenty-six patients (age: 13.39 years) with nonextraction fixed orthodontic treatment were evaluated at pretreatment and posttreatment (52 cone-beam computed tomographies). **Materials and Methods:** The maxillary and mandibular incisors (416 teeth) were evaluated for the pretreatment predictors such as the labial and palatal (lingual) cortical plate thickness, width of the mandibular symphysis/maxillary alveolus and cancellous bone, position of the root apex in cancellous/cortical bone, and treatment factors such as distance of root to the labial and palatal (lingual) outer and inner cortical plate and incisor inclination. **Statistical Analysis Used:** Statistical analyses were performed with R software at a 0.05 significance level. Each parameter was compared between pretreatment and posttreatment by a paired *t*-test, and the association to root resorption was performed using a regression model. **Results:** Clinically significant (>1 mm) root resorption was observed in 35% of all mandibular incisors and 52% of all maxillary incisors. Width of cancellous bone, position of the root apex in cortical bone, proximity of the root apex to the labial and palatal (lingual) outer cortical plate, lingual inner cortical plate, and proclination of incisors were significant factors associated with EARR. **Conclusions:** Proximity to the cortical plates and proclination of incisors are associated with increased EARR.

Keywords: *Cone-beam computed tomography, external apical root resorption, root resorption*

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Introduction

External apical root resorption (EARR) is an unfavorable side effect of orthodontic treatment.[1-3] EARR is a multifactorial process and often in clinical scenarios, it is a combination of genetic predisposition, biological process, orthodontic biomechanics, and force systems.[4] Radiographic assessment of EARR in the past has revealed conflicting findings in the literature.[5-7] Previous studies have reported that conventional radiography may underestimate or overestimate the amount of root structure loss.[5-7] With the advent of cone-beam computed tomography (CBCT), a three-dimensional assessment of the maxillomandibular structures can be performed accurately without magnification and distortion.[8] Studies using different radiographic techniques have found that maxillary incisors are more prone to EARR with orthodontic treatment.[9,10] In a recent systematic review of the comparison of root resorption with different treatment techniques, it was found that maxillary incisors undergo more EARR than other teeth.[11]

In contemporary orthodontics, about 90% of cases are treated nonextraction approach.[12] The correction of malocclusion with nonextraction treatment primarily relies on anteroposterior expansion or the proclination of the maxillary and mandibular incisors and transverse arch expansion to relieve the crowding and achieve the necessary alignment of teeth.[13] The contemporary literature shows contradictory results on whether the proclination of the maxillary and mandibular incisors can lead to EARR or not.[14,15] Ricketts suggested that the buccal root torque of maxillary molars can help to stabilize the teeth against the cortical bone to increase anchorage.[16] However, Handelman has suggested that moving the incisor roots into the cortical plates can lead to EARR.[17] The relationship

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between the EARR of the maxillary and mandibular incisor and proximity to the labial and lingual cortical plate has not been adequately investigated. Furthermore, the effect of cortical plate thickness on EARR is yet unknown. In addition, only the distance from the outer cortical plates has been identified in the previous studies and the distance of incisor roots from the inner cortical plates and its effect on root resorption has not been identified.[18]

The objectives of the current study were to evaluate the association of the pretreatment predictors such as the width of maxillary alveolus and mandibular symphysis, width of cancellous bone, and thickness of cortical plates with EARR. In addition, the study aimed to assess the effects of the treatment factors such as the effects of the proximity of the labial and lingual cortical plates on EARR in the maxillary and mandibular incisors in patients who underwent nonextraction orthodontic treatment. In this study, we tried to answer the clinical question of whether pretreatment incisor root position in the cancellous bone or cortical bone has an impact on EARR. In addition, the objective of this study was to evaluate the effect of change in the inclination of the maxillary and mandibular incisors on EARR with nonextraction. Our null hypothesis was that there is no difference in the EARR with the proximity of the roots to the cortical plates and change in inclination of the maxillary and mandibular incisors.

Materials and Methods

This retrospective study was undertaken at the University of Connecticut Health (the IRB determined that the project is not human subject research as it included a retrospective analysis of deidentified records). All the patients were treated with preadjusted edgewise appliances. The inclusion criteria were the presence of pretreatment and posttreatment CBCT, nonextraction orthodontic treatment plan, age between 12 and 15 years, absence of periodontal disease, absence of genetic abnormalities, absence of cleft and craniofacial anomalies, no previous orthodontic intervention, absence of any previous history of trauma to the incisors, no root dilacerations and anomalies, no impacted canines, and no missing permanent teeth. Patients with systemic illness, teeth with endodontic treatment, preexisting root resorption, and younger than 12 years were excluded so that the root development of incisors was completed. The sagittal skeletal patterns of the patients are described in Supplementary Table 1. Sixty CBCTs from 30 patients were evaluated at pretreatment (T1) and posttreatment (T2). Four patients were excluded due to motion artifacts. Fifty-two CBCTs (26 pretreatment and 26 post-treatment, age: 13.39 years) were analyzed in the study. The maxillary and mandibular incisors abbreviated as UL2 and UR2 – maxillary left and right lateral incisors, respectively, UL1 and UR1 – maxillary left and right central incisors, LL2 and LR2 – mandibular left and right lateral incisors, and LL1 and LR1 – mandibular left and right central incisors, respectively, were evaluated for root resorption leading to a total of 416 teeth. All the patients were informed regarding the exposure to radiation with CBCT. The potential risks from radiation exposure with CBCTs were minimal. For CBCTs, the radiation dose can be as low as 50 μSv,[19] and the yearly limit of effective dosage for infrequent radiation exposure is 5 mSv.[20] This is a retrospective evaluation, and none of the patients were exposed to radiation for the purpose of this study.

All the CBCTs were obtained with the same machine and protocol (iCAT Imaging Sciences International, Hartfield, PA; 0.3 voxels, 8.9 s, 120 kV, and 20 mA). The first CBCT was recorded at the start of orthodontic treatment (pretreatment; T1), and the second CBCT was recorded at the end of orthodontic treatment (posttreatment; T2). The average treatment time from pretreatment (T1) to posttreatment (T2) was 1.9 years ± 6 months. The digital imaging and communication in medicine data were exported to Dolphin 11.9 Version 11.9 (Dolphin Imaging and Management Solutions, Chatsworth, Calif) to reconstruct the CBCTs. The CBCTs were oriented in a standardized manner with the Frankfort horizontal plane, transporionic plane, and skeletal midline. The incisal edge and root apex were identified in the sagittal section and confirmed in the axial and coronal sections. Similarly, all the landmarks were identified in the multiplanar slices.

The incisor length was measured from the incisal edge to the root apex in the sagittal slice, and EARR was identified as the decrease in the incisor length from pretreatment (T1) to posttreatment [T2; Figure 1]. If EARR was found to be >1 mm, it was considered to be clinically significant root resorption.[21] The distance of the root apex to the inner and outer cortical plates on the labial and lingual was determined to identify the proximity of the root to the cortical plates. The width of the mandibular symphysis and maxillary alveolus was evaluated as the distance between the labial and lingual outer cortical plates, and the width of cancellous bone was measured as the distance between the labial and lingual inner cortical plates. The cortical plate thickness was analyzed as the distance between the labial inner and outer cortical plates and the palatal (lingual) inner and outer cortical plates. The mandibular symphysis and maxillary alveolus were divided into two zones: Zone 1 – the area containing cancellous bone between the labial and lingual inner cortical plates and Zone 2 – the area constituting cortical bone from the inner cortical plate to the outer cortical plate on labial and lingual aspects [Figure 1]. The pretreatment position of the root apex whether in Zone 1 or Zone 2 was recorded.

The inclination of incisors was measured with the help of the clipping tool Dolphin to clip the CBCT volume until the incisal edge and root apex of the specific incisor [Figure 2a]. The landmarks, identified in the multiplanar reconstruction, were used to draw the long axis

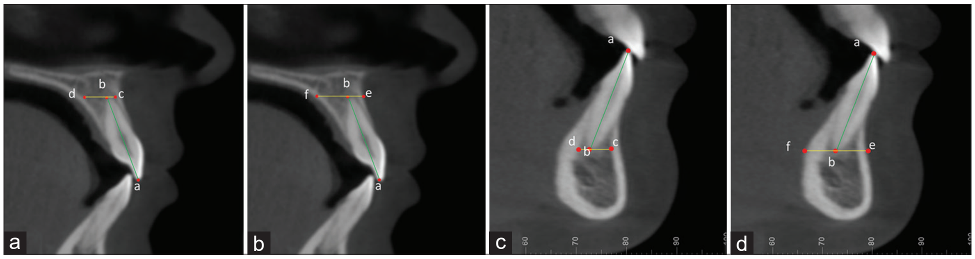
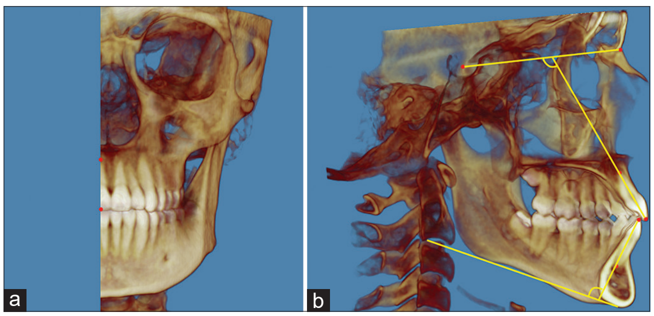


Figure 1: Measurements of the proximity to the inner and outer cortical plates; (a and c) a - Incisal tip, b - Incisal root apex, c - inner cortical plate labial, d - inner cortical plate palatal (lingual), ab - incisor length, bc - distance of the root apex to the labial inner cortical plate, bd - distance of the root apex to the palatal (lingual) inner cortical plate, cd - width of cancellous bone; (b and d) e - labial outer cortical plate, f - palatal (lingual) outer cortical plate, be - distance of the root apex to the labial outer cortical plate, bf - distance of the root apex to the palatal (lingual) outer cortical plate, ef - width of the maxillary alveolus and mandibular symphysis; ce - thickness of the labial cortical plate; df - thickness of the palatal (lingual) cortical plate. The area between the labial and lingual inner cortical plates was defined as Zone 1 (cancellous bone 0 and the area between the inner and outer cortical plates was defined as Zone 2 (cortical bone)



Figures 2: (a) Clipping of the cone-beam computed tomography; (b) Measurement of inclination of maxillary incisor to the Sella–Nasion plane defined from Sella (center of Sella turcica) to Nasion (midpoint on the frontonasal suture) and mandibular incisor to mandibular plane defined from Gonion (most posteroinferior point of angle of mandible) to Menton (most inferior point on mandibular symphysis)

for the incisors, and the inclination of the maxillary right and left lateral and central incisors was measured with the Sella–Nasion (SN) plane. Similarly, the clipping of CBCT was performed to measure the inclination of mandibular incisors with respect to the mandibular plane (Gonion–Menton) in the pretreatment and posttreatment CBCTs [Figure 2b]. The left mandibular plane was used as a reference for measurement of the mandibular incisor inclination in pretreatment and posttreatment CBCTs for reliability. The increase in the inclination of incisors from T1 to T2 was observed as proclination and the decrease in inclination was observed as retroclination.

All the measurements were performed by a single investigator. After 4 weeks, 80 incisors in 10 randomly selected CBCTs were analyzed by the same evaluator for intra-observer reliability and by another investigator for interobserver reliability.

Statistical analysis

It was determined that to achieve 80% power at the 5% significance level, 26 samples will be needed to detect the association between root resorption and distance to the palatal (lingual) cortical plate. Parameters were descriptively summarized by the mean and standard deviation (SD) or frequencies and percentages for each incisor at T1 and T2. Each parameter was compared between pretreatment and posttreatment by a paired *t*-test, and the association to root resorption was performed using a linear regression model. All the statistical analyses were performed in Version 3.5.2; R Core Team, Vienna, Austria.[22] A $P < 0.05$ was deemed to be statistically significant. The intraclass correlations coefficient and Dahlberg's method were used to analyze the reliability and method error for intra-rater measurements and inter-rater measurements.[23]

Results

The intraclass coefficients indicated good reliability for the intra-rater and inter-rater measurements. The method error as estimated by Dahlberg's method is shown in Supplementary Table 2. The mean and SDs of the pretreatment predictors for EARR are shown in Table 1. Table 2 shows the pretreatment and posttreatment measurements for the treatment factors for the maxillary and mandibular incisors.

EARR was statistically significant in all maxillary and mandibular incisors and varied from 0.79 to 1.47 mm [$P < 0.05$, Table 2]. Clinically significant (>1 mm) EARR was observed in 35% of all mandibular incisors and 52% of all maxillary incisors. The percentage of incisors with severe EARR (>3 mm) was 3% in mandibular incisors and 8% in maxillary incisors [Table 3].

The distance of the root apex to the lingual outer cortical plate and the lingual inner cortical plate was significantly decreased from T1 to T2 for the mandibular and maxillary incisors [$P < 0.05$, Table 2]. The mean angulation for lower incisors to the mandibular plane and maxillary incisors to the SN plane was increased significantly from T1 to T2 for the mandibular and maxillary incisors [$P < 0.05$, Table 2].

Tables 4 and 5 show that a significant association ($P < 0.05$) was found between the pretreatment predictors of the width of cancellous bone and EARR for UL2, with the regression coefficient (RC) being 0.22, pretreatment position of the root apex in Zone 2 (cortical bone), and EARR for LR1 (RC − 0.87) and UL2 (RC − 1.13). A significant association was observed between the treatment factors of

Table 1: Mean and standard deviation of pretreatment predictors for root resorption

	LR2	LR1	LL2	LL1	UR2	UR1	UL1	UL2
Pretreatment predictors (mean±SD)								
Labial cortical plate thickness	2.42±0.68	2.19±0.55	2.49±0.65	2.35±0.63	1.99±0.65	2.48±1.05	2.2±1.87	2.25±0.94
Palatal (lingual) cortical plate thickness	3.11±0.62	3.14±0.67	3.26±0.71	3.21±0.75	2.18±0.46	2.22±0.53	2.58±0.95	2.15±0.65
Width of the mandibular symphysis/ maxillary alveolus	9.86±1.74	9.78±1.82	9.91±1.79	9.8±1.81	11.73±2.49	13.85±1.99	14.47±2.41	11.72±2.39
Width of cancellous bone	4.33±1.49	4.45±1.65	4.16±1.53	4.24±1.73	7.56±2.42	9.15±2.54	9.69±2.58	7.32±2.3
Position of the root apex in the cortico-cancellous zones, *n* (%)								
Zone 2 (cortical bone)	10 (40)	5 (20)	11 (44)	10 (40)	6 (24)	9 (36)	6 (24)	7 (28)
Zone 1 (cancellous bone)	15 (60)	20 (80)	14 (56)	15 (60)	19 (76)	16 (64)	19 (76)	18 (72)

SD: Standard deviation; LR2: Mandibular right lateral incisor; LR1: Mandibular right central incisor; LL2: Mandibular left lateral incisor; LL1: Mandibular left central incisor; UR2: Maxillary right lateral incisor; UR1: Maxillary right central incisor; UL1: Maxillary left central incisor; UL2: Maxillary left lateral incisor

Table 2: Mean and standard deviation of treatment factors at pretreatment for the maxillary and mandibular incisors (T1)

	Mandibular incisors			*P**	Maxillary incisors			*P**
	Pretreatment (T1), mean±SD	Posttreatment (T2), mean±SD	T2–T1, mean (95% CI)		Pretreatment (T1), mean±SD	Posttreatment (T2), mean±SD	T2–T1, mean (95% CI)	
Incisor length	22.09±1.80	21.21±1.59	−0.88 (−1.07–−0.69)	<0.001*	23.00±2.09	21.75±2.04	−1.25 (−1.46–−1.03)	<0.001*
Distance of the root apex to the labial outer cortical plate	4.62±1.36	4.30±1.80	−0.32 (−0.57–−0.07)	0.012*	4.04±1.53	3.95±1.68	−0.08 (−0.42–0.26)	0.631
Distance of the root apex to the labial inner cortical plate	2.26±1.35	2.34±1.66	0.09 (−0.17–0.34)	0.500	1.81±1.43	1.83±1.84	0.02 (−0.30–0.34)	0.901
Distance of the root apex to the palatal (lingual) outer cortical plate	5.21±1.19	4.07±1.30	−1.15 (−1.40–−0.90)	<0.001*	8.90±2.26	7.03±2.24	−1.87 (−2.31–−1.44)	<0.001*
Distance of the root apex to the palatal (lingual) inner cortical plate	2.03±1.02	1.20±1.26	−0.83 (−1.08–−0.57)	<0.001*	6.62±2.15	4.63±2.16	−1.99 (−2.42–−1.57)	<0.001*
Inclination of incisors	88.32±6.50	92.19±7.65	3.87 (2.79–4.95)	<0.001*	99.94±6.96	108.53±6.50	8.59 (6.97–10.2)	<0.001*

*Significant at $P<0.05$. SD: Standard deviation; 95% CI: 95% Confidence interval

Table 3: Percentage of clinically significant root resorption in the mandibular and maxillary incisors

Group	Mandibular incisors (%)	Maxillary incisors (%)
Nonclinically significant root resorption (<1 mm)	62	40
Clinically significant root resorption (≥1 mm)	35	52
Severe root resorption (≥3 mm)	3	8
Total	100	100

the decreased distance of the root apex to the labial outer cortical plate for LR1 (RC 0.31) and UR2 (RC 0.26), decreased distance of the root apex to the lingual outer cortical plate LR2 (RC 0.38), palatal outer cortical plate UR2 (RC 0.21), UR1 (RC 0.25), and UL1 (RC 0.19), decreased distance of root apex to the palatal inner cortical plate UR2 (RC 0.23), and proclination of incisors for LR2 (RC − 0.16 mm), LL2 (RC − 0.12 mm), and LR1 (RC − 0.08 mm).

Discussion

Our null hypothesis was rejected as we found a significant association between EARR and proximity to the cortical plate of the maxillary incisors and between EARR and proclination of the mandibular incisors. We found that the maxillary incisors (52%) showed a higher incidence of clinically significant EARR than the mandibular incisors [35%; Table 3]. In addition, the amount of EARR

Table 4: Regression analysis for mandibular incisor root resorption

	LR2		LR1		LL2		LL1	
	Beta (95% CI)	*P*	Beta (95% CI)	*P*	Beta (95% CI)	*P*	Beta (95% CI)	*P*
Pretreatment predictors								
Labial cortical plate thickness	−0.25 (−0.84–0.34)	0.384	−0.25 (−0.85–0.34)	0.387	0.09 (−0.65–0.83)	0.798	−0.07 (−0.75–0.6)	0.825
Lingual cortical plate thickness	−0.31 (−0.95–0.34)	0.336	−0.04 (−0.53–0.45)	0.872	−0.25 (−0.92–0.41)	0.44	−0.16 (−0.72–0.4)	0.567
Width of the mandibular alveolus	−0.06 (−0.29–0.17)	0.582	−0.07 (−0.25–0.11)	0.442	−0.22 (−0.47–0.04)	0.089	0.05 (−0.18–0.28)	0.657
Width of cancellous bone	0.02 (−0.25–0.29)	0.887	−0.05 (−0.25–0.15)	0.624	−0.26 (−0.55–0.04)	0.082	0.1 (−0.15–0.34)	0.425
Position of the root apex in cortico-cancellous bone zone 2 versus zone 1	0.39 (−0.4–1.18)	0.321	−0.87 (0.16–1.59)	0.019*	0.15 (−0.8–1.1)	0.74	0.46 (−0.37–1.29)	0.262
Treatment factors								
Distance of the root apex to the labial outer cortical plate	0.18 (−0.17–0.53)	0.296	0.31 (0.04–0.58)	0.029*	0.01 (−0.32–0.34)	0.937	0.26 (−0.03–0.54)	0.08
Distance of the root apex to the labial inner cortical plate	0.11 (−0.23–0.46)	0.502	0.26 (0–0.52)	0.05	0.01 (−0.31–0.33)	0.942	0.25 (−0.05–0.56)	0.094
Distance of the root apex to the lingual outer cortical plate	0.38 (0.05–0.71)	0.025*	−0.11 (−0.41–0.18)	0.429	0.17 (−0.13–0.46)	0.249	0.16 (−0.18–0.5)	0.336
Distance of the root apex to the lingual inner cortical plate	0.32 (−0.01–0.66)	0.057	−0.11 (−0.45–0.22)	0.491	0.14 (−0.13–0.42)	0.299	0.05 (−0.28–0.38)	0.774
Proclination of incisors	−0.16 (−0.27–−0.04)	0.009*	−0.08 (0.01–0.14)	0.021*	−0.12 (−0.21–−0.02)	0.019*	0.07 (−0.03–0.17)	0.174
Retroclination of incisors	0.62 (−0.08–1.33)	0.074	−0.28 (−1.19–0.63)	0.438	0.04 (−0.15–0.23)	0.432	0.11 (−0.54–0.75)	0.699

*Significant at $P<0.05$. 95% CI: 95% Confidence interval; LR2: Mandibular right lateral incisor; LR1: Mandibular right central incisor; LL2: Mandibular left lateral incisor; LL1: Mandibular left central incisor

was greater in the maxillary incisors than in the mandibular incisors. Clinically significant EARR (>1 mm), and severe EARR (>3 mm) were also higher in the maxillary incisors compared to the mandibular incisors [Table 3].

The maxillary and mandibular incisors were analyzed in this study as these teeth have been found to undergo EARR more frequently than other teeth in orthodontic patients.[11,24,25] The inclusion criteria were 12–15 years to select a homogeneous sample that had completed the root development of incisors and is representative of the common orthodontic population. We did not select a population over 15 years of age to reduce any external effects due to aging which may lead to increased EARR.[2] The landmarks identified on multiplanar reconstruction were used to construct lines for measuring the length and inclination of the teeth. Using this approach increased the accuracy of the measurements by avoiding the artifacts that may be created during the volumetric construction of CBCTs.

We observed that in certain cases, the incisor roots were found to be completely outside of the alveolar housing posttreatment [Figure 3]. In such instances, where the root apex of the incisor traverses the entire thickness of cortical bone, it will get in contact with the inner cortical plate first, before touching the outer cortical plates. Thus, it is important to identify the proximity to both, inner and outer cortical plates and the thickness of cortical plates, to evaluate its effect on EARR. Ten Hoeve and Mulie evaluated EARR with orthodontic treatment and Begg therapy and showed that palatal root torquing of the maxillary incisors leads to increased EARR.[26] In addition, in a study assessing patients with Class III malocclusion, it was found that severe EARR was associated with the root apex being close to the palatal cortical plate.[27] Similarly, in our study, we found that in patients with Class I malocclusion treated with nonextraction orthodontic therapy, the amount of EARR was significantly correlated with the proximity of roots to the cortical plate for UR2, UR1, and UL1 indicating increased EARR with a decreased distance of root apex to the palatal outer cortical plate [$P < 0.05$, Table 5]. In addition, we found that the distance of the root apex to the inner cortical plate was significantly correlated with EARR for UR2 [$P < 0.05$, Table 5]. This is an important finding to be considered during orthodontic treatment, especially for Class III camouflage cases, as maxillary incisors are often proclined to compensate for the skeletal discrepancy, and as a result, the incisor roots come in contact with the palatal cortical plate.[27] Thus, clinicians should consider the findings of increased EARR for UR2, UR1, and UL1 with proximity to the cortical plate and consider moving the teeth to be placed within the cancellous bone so as to decrease the chance of root resorption.

Table 5: Regression analysis for maxillary incisor root resorption

	UR2		UR1		UL1		UL2	
	Beta (95% CI)	*P**	Beta (95% CI)	*P**	Beta (95% CI)	*P**	Beta (95% CI)	*P**
Pretreatment predictors								
Labial cortical plate thickness	−0.22 (−0.9–0.46)	0.512	0.16 (−0.27–0.59)	0.451	−0.13 (−0.38–0.11)	0.277	0.34 (−0.19–0.87)	0.194
Palatal cortical plate thickness	−0.28 (−1.24–0.67)	0.549	−0.41 (−1.25–0.42)	0.318	−0.33 (−0.8–0.15)	0.17	−0.23 (−1.02–0.57)	0.562
Width of the maxillary alveolus	−0.14 (−0.31–0.03)	0.108	−0.16 (−0.38–0.05)	0.132	−0.1 (−0.29–0.09)	0.307	−0.17 (−0.37–0.04)	0.102
Width of cancellous bone	−0.12 (−0.3–0.06)	0.177	−0.11 (−0.28–0.06)	0.202	0.03 (−0.15–0.21)	0.745	0.22 (−0.42–−0.02)	0.035*
Position of the root apex in cortico-cancellous bone zone 2 versus zone 1	0.08 (−0.94–1.11)	0.868	−0.09 (−1.02–0.84)	0.842	0.98 (−0.01–1.97)	0.052	−1.13 (−2.14–−0.11)	0.031*
Treatment factors								
Distance of the root apex to the labial outer cortical plate	0.26 (−0.49–−0.02)	0.035*	−0.19 (−0.51–0.13)	0.227	−0.09 (−0.38–0.2)	0.517	−0.15 (−0.38–0.08)	0.191
Distance of the root apex to the labial inner cortical plate	−0.16 (−0.4–0.08)	0.178	0.07 (−0.2–0.35)	0.573	−0.25 (−0.54–0.05)	0.094	−0.17 (−0.52–0.19)	0.348
Distance of the root apex to the palatal outer cortical plate	0.21 (0.04–0.38)	0.018*	0.25 (0.06–0.43)	0.012*	0.19 (0–0.39)	0.046*	0.14 (−0.09–0.37)	0.216
Distance of the root apex to the palatal inner cortical plate	0.23 (0.03–0.43)	0.024*	0.2 (−0.01–0.41)	0.059	0.13 (−0.07–0.32)	0.205	0.13 (−0.09–0.35)	0.224
Proclination of incisors	0.01 (−0.05–0.06)	0.835	−0.03 (−0.13–0.08)	0.62	−0.02 (−0.14–0.1)	0.75	−0.06 (−0.13–0)	0.058
Retroclination of incisors	−0.13 (−2.88–2.63)	0.667	NA	NA	−0.02 (−0.4–0.36)	0.878	−0.03 (−2.74–2.69)	0.916

*Significant at $P<0.05$. 95% CI: 95% Confidence interval, UR2: Maxillary right lateral incisor; UR1; Maxillary right central incisor; UL1: Maxillary left central incisor; UL2: Maxillary left lateral incisor, NA: Not available

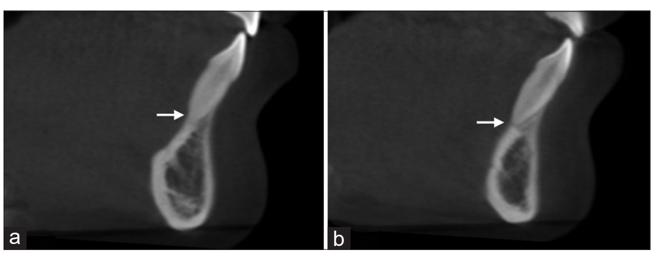


Figure 3: (a and b) Incisor roots traversing the entire thickness of cortical bone, through the lingual inner cortical plate and lingual outer cortical plate

The proximity of the root apex to the lingual cortical plate was significantly associated with EARR for LR2. A decrease in the distance of the root apex to the lingual cortical plate by 2.63 mm would be associated with an EARR of 1 mm [$P < 0.05$, Table 4]. In addition, we observed increased EARR by 1.13 mm for UL2 and 0.88 mm for LR1 if the roots were located in Zone 2 (cortical bone) at pretreatment compared to Zone 1 (cancellous bone). This indicates that the pretreatment location of the root apex within the cortical plate is a significant factor for EARR and patients should be advised of the possibility of increased root resorption if the roots are found to be in contact with cortical plates at pretreatment radiographic evaluation. In addition, we found that the decreased distance of the root apex to the

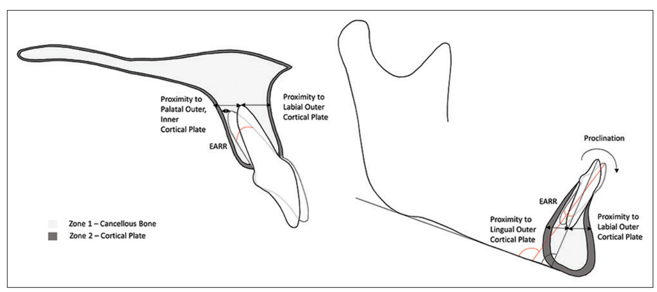
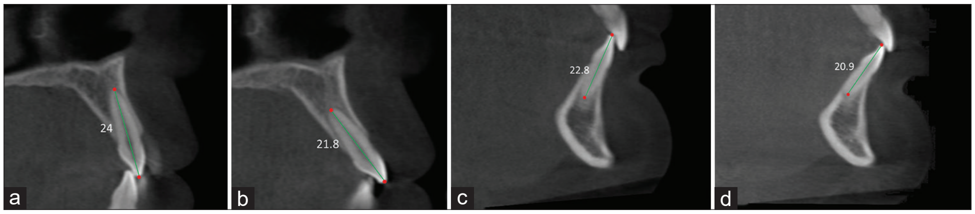


Figure 4: Schematic figure demonstrating the treatment factors relating to root resorption in the maxillary and mandibular incisors. The solid line represents pretreatment and the dotted line shows the posttreatment change. Maxillary incisors: Proximity to the palatal (lingual) outer cortical plate, proximity to the palatal (lingual) inner cortical plate, proximity to the labial outer cortical plate. Mandibular incisors: Proclination of the mandibular incisors, proximity to the lingual outer cortical plate, and proximity to the labial outer cortical plate

labial outer cortical plate showed a significant association with EARR for UR2 and LR1 [$P < 0.05$, Tables 4 and 5]. This suggests that increased proximity to the labial cortical plate with orthodontic treatment is a significant factor for root resorption. Thus, it may be prudent to periodically check for EARR in certain clinical situations such as Class III malocclusion treated with orthodontic camouflage, as it frequently leads to retroclination of lower incisors and consequently increased proximity of the roots to the



Figures 5: (a and b) Pretreatment and posttreatment images cone-beam computed tomography (CBCT) images showing root resorption of UR1 with proximity to the palatal (lingual) cortical plate; (c and d) pretreatment and posttreatment CBCT images showing root resorption of LL1 with proclination of the lower incisor

labial cortical plate.[27] An interesting finding in our study was that the distance of the root apex to both labial and palatal (lingual) cortical plates was found to be decreased. This results because of the decrease in the labiolingual width of alveolar bone due to the alveolar bone loss with orthodontic treatment.[28]

The inclination of the mandibular incisors was significantly correlated with EARR for LR1, LL1, and LL2 [$P < 0.05$, Table 4]. In our study, the inclination of the mandibular and maxillary incisors increased significantly at T2 compared to T1 [$P < 0.05$, Table 2]. Proclination of the mandibular incisors is an expected outcome with nonextraction orthodontic therapy.[13,29] The regression analysis showed an increase of EARR by 0.08–0.16 mm with every 1° increase in the inclination of mandibular incisors [Table 4]. Thus, this implies that patients with increased mandibular crowding may be at risk for increased root resorption as a result of pronounced proclination of the mandibular incisors with nonextraction therapy. These treatment factors leading to increased EARR in the maxillary and mandibular incisors are described with a schematic diagram in Figure 4. Figure 5 shows CBCT images of cases with root resorption in proximity to the palatal (lingual) cortical plate and proclination of incisors.

The information regarding the effect of cortical and cancellous bone width on EARR is not available, and thus, to differentiate and observe the effect of dimensions of cortical bone and cancellous bone on EARR, we employed a novel measurement to our study of the width of cancellous bone. In addition, we studied the effect of the labial and palatal (lingual) cortical plate thickness on EARR and found that cortical plate thickness was not a significant factor for EARR. In our study, the maxillary alveolus width and mandibular symphyseal width were not found to be significant factors for EARR. This is in contrast to Handelman[17] who suggested that decreased width of the maxillary alveolus is a risk factor for root resorption. However, our results indicated that the width of the cancellous bone was a significant factor for EARR [$P < 0.05$, Table 5]. This is because a narrower width of cancellous bone may increase the chances of the incisor root being in contact with the palatal cortical plate as a result of orthodontic treatment. Thus, clinicians should be aware of the teeth exhibiting a higher amount of root resorption and the predicting factors so that they can be vigilant during the orthodontic treatment and observe periodically for any signs of EARR.

Limitations and future study prospects

A limitation of this study was its retrospective design. In addition, there were variations in the susceptibility of the teeth to root resorption with proximity to the cortical plate and proclination of teeth. Furthermore, the effect of ethnic and gender variations on the width and thickness of the maxilla and mandible have not been taken into consideration in this study. Another limitation is the lack of universal practical applicability of the results in the present scenario, given the cost-ineffectiveness of CBCT. Future studies can evaluate the incidence of root resorption in patients with different age distributions.

Conclusions:

• Proximity to the cortical plates and proclination of incisors are found to be associated with increased risk of EARR and this should be kept in consideration while treatment planning an orthodontic with increased crowding through non-extraction mechanotherapy.

• Pretreatment factors such as the width of cancellous bone and pretreatment location of root apex in the cortical bone were identified as significant factors for root resorption.

• Treatment factors such as proximity to labial outer cortical plate, palatal or lingual outer cortical plate, palatal inner cortical plate, and proclination of mandibular incisors showed a significant association with root resorption.

• Clinically significant (>1 mm) External Apical Root Resorption (EARR) and severe EARR was observed more frequently in maxillary incisors than mandibular incisors.

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Conflicts of interest

There are no conflicts of interest.

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Supplementary Tables

Supplementary Table 1: Distribution of sagittal skeletal relationship in the study patients

Type of malocclusion	Percentage
Class I	75
Class II	15
Class III	10
Total	100
Parameter	**Mean±SD**
ANB	1.85 (2.24)

SD: Standard deviation

Supplementary Table 2: Intraclass coefficients and method error analysis with Dahlberg's formula for intra- and inter-rater reliability analysis

	Inter-rater reliability (ICC)	Inter-rater Dahlberg method error analysis	Intra-rater reliability (ICC)	Intra-rater Dahlberg method error analysis
Incisor length	0.934 (0.906–0.954)	0.17	0.937 (0.909–0.956)	0.16
Labial cortical plate thickness	0.91 (0.872–0.937)	0.04	0.908 (0.869–0.936)	0.05
Palatal cortical plate thickness	0.929 (0.898–0.95)	0.04	0.905 (0.866–0.934)	0.06
Width of the mandibular symphysis/maxillary alveolus	0.984 (0.977–0.989)	0.11	0.985 (0.979–0.99)	0.11
Width of cancellous bone	0.988 (0.983–0.992)	0.1	0.988 (0.982–0.992)	0.11
Distance of the root apex to the labial outer cortical plate	0.959 (0.941–0.972)	0.1	0.973 (0.962–0.982)	0.07
Distance of the root apex to the palatal outer cortical plate	0.956 (0.937–0.97)	0.32	0.988 (0.983–0.992)	0.08
Distance of the root apex to the labial inner cortical plate	0.955 (0.936–0.969)	0.11	0.959 (0.941–0.971)	0.1
Distance of the root apex to the palatal inner cortical plate	0.984 (0.977–0.989)	0.12	0.986 (0.979–0.99)	0.1
Inclination of incisors	0.987 (0.98–0.991)	1.53	0.99 (0.985–0.993)	1.18
Position of the root apex in the cortico-cancellous zones	1 (1–1)	NA	1 (1–1)	NA

ICC: Intraclass coefficients; NA: Not available