Original Article

Apical root displacement is a critical risk factor for apical root resorption after orthodontic treatment

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ABSTRACT

Objectives: To identify risk factors for apical root resorption (ARR) of maxillary and mandibular incisors using mathematical quantification of apical root displacement (ARD) and multiple linear mixed-effects modeling.

Materials and Methods: Periapical radiographs of maxillary and mandibular incisors and lateral cephalograms of 135 adults were taken before and after orthodontic treatment. ARR was measured on the periapical radiographs, and movement of central incisors was evaluated on the superimposed pre- and posttreatment lateral cephalograms. ARD was mathematically calculated from pretreatment tooth length, inclination change, and movement of the incisal edge. Linear mixed-effects model analysis was performed to identify risk factors for ARR, and standardized coefficients (SCs) were calculated to investigate the relative contribution of the risk factors to ARR.

Results: Vertical ARD showed the highest SCs for both maxillary and mandibular incisors. Horizontal ARD showed the second highest SC for mandibular incisors but was not significantly correlated with the ARR of maxillary incisors. When horizontal and vertical ARDs were included in the mixed-effects model, the use of self-ligating brackets was significantly correlated with increased ARR of mandibular incisors.

Conclusions: ARD is a critical factor for ARR after orthodontic treatment. Careful monitoring of ARR is recommended for patients requiring significant ARD of incisors. (*Angle Orthod.* 2018;88:740–747.)

KEY WORDS: Apical root resorption; Apical root displacement; Orthodontic treatment; Mathematical calculation; Mixed-effects model

INTRODUCTION

External apical root resorption (ARR) is a common iatrogenic side effect of orthodontic treatment. Although histologic evidence of root resorption has been found in more than 90% of orthodontic patients, the prevalence of severe ARR that may jeopardize the longevity of teeth has been reported as affecting 1% to 5% of teeth.[1] Therefore, identification of risk factors for

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Table 1. Patient Characteristics[a]

Characteristic	Conventional Brackets (n = 57), Mean ± SD or n (%)	Self-Ligating Brackets (n = 78), Mean ± SD or n (%)	Total (N = 135), Mean ± SD or n (%)
Age, y	25.5 ± 4.5	26.3 ± 4.7	25.9 ± 4.6
Sex			
Male	20 (35.1)	24 (30.8)	44 (32.6)
Female	37 (64.9)	54 (69.2)	91 (67.4)
Extraction			
No	33 (57.9)	42 (53.8)	75 (55.6)
Yes	24 (42.1)	36 (46.3)	60 (44.4)
Initial tooth length, mm	23.6 ± 1.5	23.3 ± 1.7	23.4 ± 1.6
Treatment duration, mo	27.1 ± 12.4	24.4 ± 8.7	25.7 ± 10.5

[a] SD indicates standard deviation.

ARR after orthodontic treatment is a critical issue in orthodontic research.

ARR is caused by the activity of odontoclasts/osteoclasts that remove necrotic hyalinized tissue during orthodontic tooth movement.[2] Thus, it is a plausible assumption that apical root displacement (ARD) is directly associated with ARR since more ARD involves resorption of a larger amount of hyalinized tissue. However, most previous studies have found only marginally significant correlations between the amount of ARD and ARR of maxillary incisors. Moreover, conflicting results have been reported with regard to the relationship between the direction of ARD and ARR; some studies have reported correlations only with horizontal displacement,[3–5] while others suggested that intrusive root movement is a strong indicator of ARR.[6,7]

Two methodologic factors have contributed to the inconsistency of those findings. The first is the accuracy of ARD measurement; even a 1-mm discrepancy can significantly affect the results because the mean amount of ARD of the maxillary incisors ranges from 1.5 to 3.0 mm.[8] Most studies evaluated ARD by substituting the pretreatment intact root apex for the posttreatment resorbed root apex on the superimposed cephalograms, but locating the root apex on a lateral cephalogram is associated with high method error.[9] ARD can be more accurately measured by mathematical calculation using the displacement of the incisor tip and inclination change, both of which are easily identified on the lateral cephalograms.

The second methodological concern is the statistical analysis. Multiple analyses are mandatory to account for interactions among various diagnostic and treatment factors. In this regard, linear regression analysis was adopted in most previous studies, in which all variables are treated as fixed effects. However, host factors, such as single-nucleotide polymorphisms in interleukin-6, also affect ARR,[10] which means that individual orthodontic patients may respond differently to the same treatment modality. A mixed-effects model can treat subjects as a random effect; thus, it is preferred over traditional statistical approaches for investigating risk factors of ARR.

Therefore, the purpose of the study was to identify risk factors for ARR of the maxillary and mandibular incisors by using mathematical quantification of ARD and multiple linear mixed-effects modeling.

MATERIALS AND METHODS

Subjects

This study was approved by the institutional review board of Gangnam Severance Hospital (No. 3-2014-0178). The power analysis showed that group sample sizes of 63 and 63 achieve 80% power to detect a difference of 0.5 mm in root resorption with estimated standard deviations of 1.0 mm and an α of .05 using a two-sided, two-sample *t*-test.

The subjects were randomly selected among patients who met the following inclusion criteria: (1) adult patients (age $>$18 years) who completed comprehensive orthodontic treatment from January 2009 to March 2013 in the Department of Orthodontics, Gangnam Severance Hospital, Seoul, South Korea; (2) patients who underwent nonextraction treatment or had their four first premolars extracted; and (3) patients treated with either conventional preadjusted brackets (Formula-R, Roth type, Tomy, Tokyo, Japan) or self-ligating brackets (Clippy-C, Roth type, Tomy). The exclusion criteria were (1) history of previous orthodontic treatment, orthognathic surgery, root canal treatment, or trauma; (2) presence of active periodontal disease or root resorption manifesting clinically or radiographically before treatment; (3) presence of an impacted tooth; (4) microdontia; (5) extraction of teeth other than the four first premolars; and (6) presence or history of oral habits such as tongue thrust and nail biting. A total of 135 patients (44 men, 91 women) who met the criteria were included in this study (Table 1).

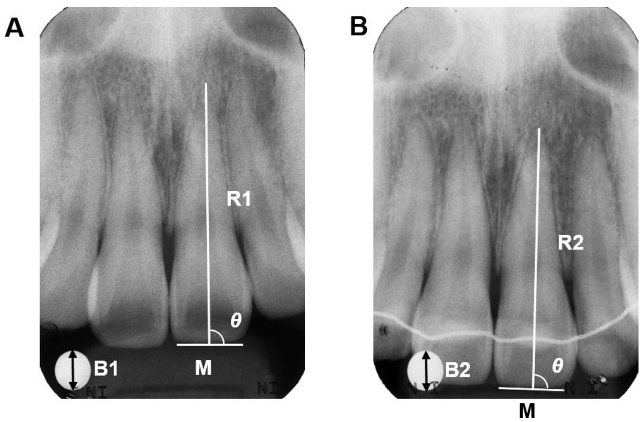

Figure 1. Measurement of apical root resorption using pretreatment periapical radiograph (A) and posttreatment periapical radiograph (B). R1 indicates pretreatment tooth length; R2, posttreatment tooth length; M, midpoint of the incisal edge; θ, intersection angle between the incisal edge and the long axis on the pretreatment radiograph; B1, pretreatment ball height; B2, posttreatment ball height.

ARR Measurements on Periapical Radiographs

Periapical radiographs were taken of the maxillary and mandibular four incisors before and after treatment using the standardized parallel cone technique. A 4-mm spherical metal ball bearing (X-ray Distortion Markers, Salvin Dental Specialties, Charlotte, NC) was attached to the film for standardization of ARR measurement. The developed films were scanned and converted to digital images at a resolution of 2400 dpi at 256 scale.

ARR was evaluated for the maxillary central incisors (U1), maxillary lateral incisors (U2), mandibular central incisors (L1), and mandibular lateral incisors (L2). Pretreatment tooth length (R1) was measured along the long axis connecting the midpoint of the incisal edge (M) and the root apex, and the intersection angle (θ) between the incisal edge and the long axis was recorded. Posttreatment tooth length (R2) was measured along the long axis originating from M with an intersection angle of θ to the incisal edge. The correction factor (CF) was calculated as the ratio of the pretreatment ball height (B1) and the posttreatment ball height (B2) to correct any differences in image magnification or distortion between pretreatment and posttreatment radiographs. ARR was calculated as follows (Figure 1):

$$CF = B1/B2$$

$$ARR = R1 - (R2 \times CF)$$

All measurements were performed using the Image J 1.43u software program (Wayne Rasband, National Institutes of Health, Bethesda, Md) with B1 height defined as 4 mm.

Evaluation of Central Incisor Movement on Lateral Cephalograms

The movement of maxillary and mandibular central incisors was evaluated on lateral cephalograms. We superimposed the tracings by means of the "best fit of anatomical structures" with a primary emphasis on the concordance of the palatal plane (ANS-PNS) and ANS for the maxilla and mandibular plane (gonion-menton) and menton for the mandible.[11]

The horizontal movement (Dx) and vertical movement (Dy) of the maxillary and mandibular central

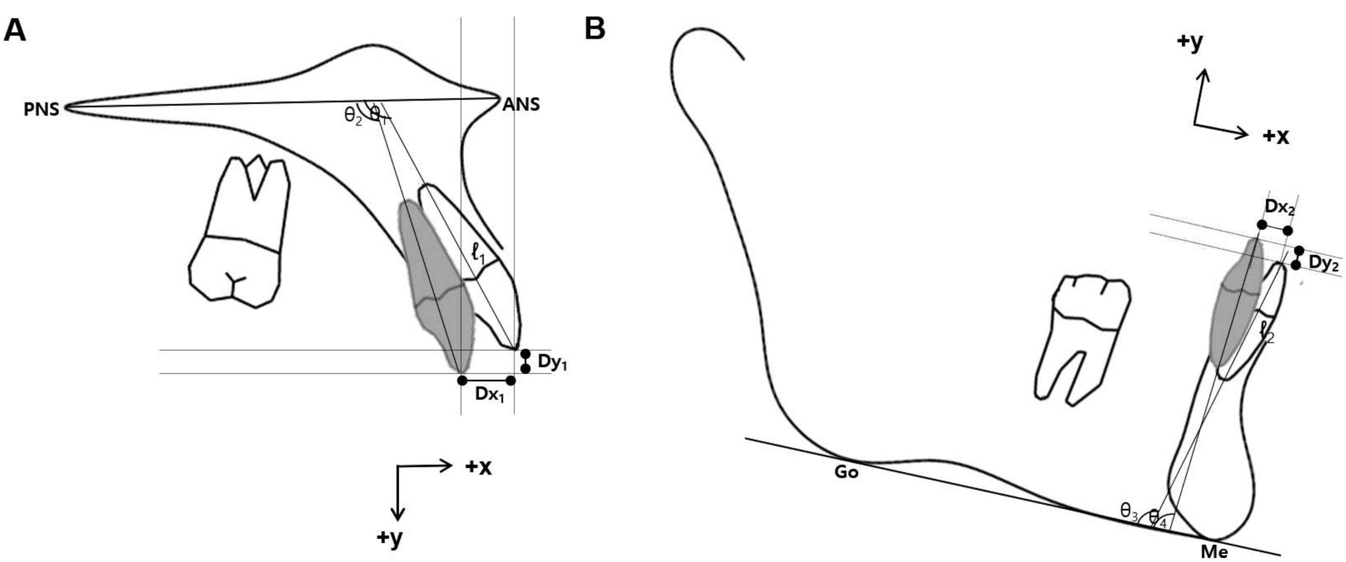

Figure 2. Evaluation of maxillary central incisor (A) and mandibular central incisor (B) movements on superimposed lateral cephalograms. ANS indicates anterior nasal spine; PNS, posterior nasal spine; Me, menton; Go, gonion; Dx, horizontal movement of the incisal edge; Dy, vertical movement of the incisal edge; θ, inclination of the central incisor to the palatal plane or mandibular plane.

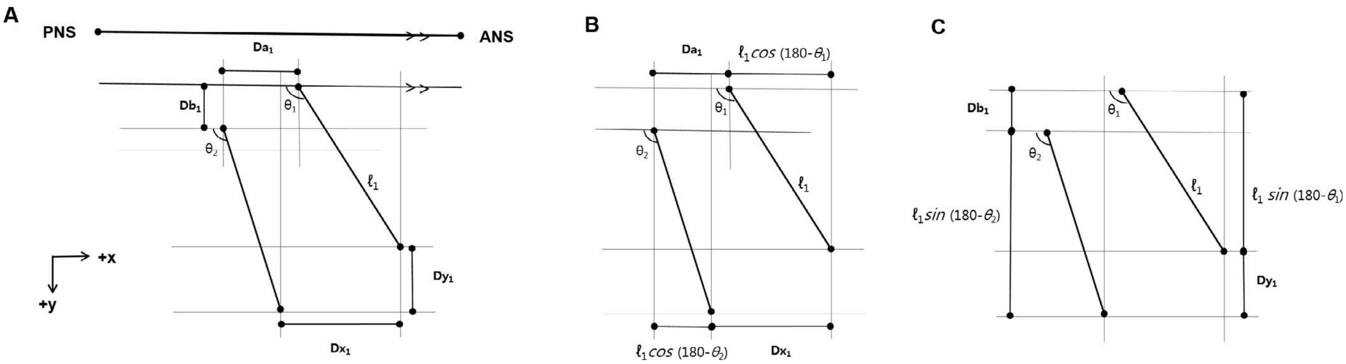

Figure 3. Schematic diagram for mathematical calculation of horizontal (B) and vertical (C) apical root displacement of maxillary central incisor. Dx indicates horizontal movement of the incisal edge; Dy, vertical movement of the incisal edge; Da, horizontal movement of the root apex; Db, vertical movement of the root apex; θ, inclination of the central incisor to the palatal plane.

incisal edges were measured using an X-Y coordinate system, defined as the x-axis parallel to the palatal plane or mandibular plane and the y-axis perpendicular to the x-axis passing through the ANS or menton. The $+$ x value was defined as the direction of protraction and the $+$ y value as the direction of extrusion. The x and y coordinates of the maxillary and mandibular incisal edges were measured on the pre- and posttreatment lateral cephalograms to calculate Dx and Dy. Furthermore, the pretreatment tooth length (ℓ) and the inclination of the central incisors (θ) to the palatal plane or mandibular plane were measured (Figure 2).

Mathematical Calculation of ARD

The horizontal movement (Da) and vertical movement (Db) of the root apices of the central incisors were mathematically calculated by Dx, Dy, ℓ, and θ as follows (Figure 3):

$$\mathrm{Da} = \mathrm{Dx} + \ell\Big(cos(180 - -\theta_1) - cos(180 - -\theta_2)\Big)$$

$$\mathrm{Db} = \mathrm{Dy} + \ell\Big(sin(180 - -\theta_1) - sin(180 - \theta_2)\Big)$$

The net movement of the root apices was calculated as follows:

$$\mathrm{Dnet} = \sqrt{\mathrm{Da}^2 + \mathrm{Db}^2}$$

Statistical Analysis

All measurements on the periapical radiographs and lateral cephalograms were repeated twice by one examiner in a 2-week interval. The repeated measurements were used to calculate intraclass correlation coefficients to examine the intraexaminer reliability. The method errors were calculated using the Dahlberg formula: $Se = \sqrt{}(\Sigma d^2/2n)$, where d is the difference between repeated measurements and n is the number of pairs of measurements.

Paired *t*-test was used to compare pre- and posttreatment tooth length measured on periapical radiographs to investigate ARR. Multiple linear mixed-effects model analysis was performed to identify the risk factors for ARR, using age, sex, tooth type, pretreatment tooth length (R1), extraction, treatment duration, bracket types, the absolute value of inclination change ($|\theta|$), and the absolute value of the amount of tooth movement as covariates. The model was assumed to have a compound-symmetry variance-covariance structure. Variance inflation factors of all models were less than 5, indicating that there was no multicollinearity problem. Standardized coefficients (SCs) were calculated for the variables with *P* value less than .05 to investigate relative contribution of the risk factors to ARR. Statistical analyses were performed at the 5% level of significance using SAS for Windows, version 9.4 (SAS Institute, Cary, NC).

RESULTS

Intraclass correlation coefficients ranged from .919 to .947, indicating excellent reproducibility of measurements. The method errors ranged from 0.18–0.28 mm for ARR and from 0.25–0.41 mm for ARD. There was no statistically significant difference between the right and left sides in all measurements ($P > .05$); thus, teeth on the right and left sides were not divided into subgroups, and the averaged measurements of the right and left sides were used for analyses.

The tooth length of all incisors decreased significantly after treatment ($P < .001$). The mean ARR of all incisors was 0.98 $\pm$ 0.32 mm (Table 2). The horizontal and vertical ARDs of the central incisors were 2.31 $\pm$ 1.62 mm and 1.70 $\pm$ 1.11 mm for the maxilla and 2.06 $\pm$ 1.12 mm and 1.62 $\pm$ 0.94 mm for the mandible, respectively (Table 3).

Table 2. Apical Root Resorption (mm)[a]

	Conventional Brackets (n = 57), Mean (SD)	Self-Ligating Brackets (n = 78), Mean (SD)	Total (N = 135), Mean (SD)	*P* Value
U1	1.09 (0.51)	1.08 (0.49)	1.09 (0.49)	.938
U2	1.13 (0.58)	1.05 (0.48)	1.08 (0.52)	.398
L1	0.77 (0.45)	0.94 (0.54)	0.87 (0.50)	.057
L2	0.81 (0.33)	0.94 (0.57)	0.88 (0.48)	.105

[a] SD indicates standard deviation; U1, maxillary central incisors; U2, maxillary lateral incisors; L1, mandibular central incisors; L2, mandibular lateral incisors.

Risk Factors for ARR Without Consideration of Tooth Movement

Multiple linear mixed-model analysis was performed on all incisors, including age, sex, tooth type (U1, U2, L1, L2), pretreatment tooth length (R1) on periapical radiographs, extraction, treatment duration, and bracket types as covariates. Variables related to tooth movement were not included because the evaluation of tooth movement on lateral cephalograms was performed only for central incisors. ARR correlated with extraction ($P < .01$), pretreatment tooth length ($P < .05$), and tooth type ($P < .001$). ARR was higher in patients with extracted premolars, longer teeth, and maxillary incisors (Table 4).

Risk Factors for ARR With Consideration of Crown Movement

Multiple linear mixed-model analysis was also performed in maxillary and mandibular central incisors separately, including age, sex, pretreatment tooth length (R1) on periapical radiographs, extraction, treatment duration, bracket types, $|\Delta\theta|$, |Dx|, and |Dy| as covariates. The ARR of maxillary central incisors correlated with extraction (SC, 1.012; $P < .05$), |Dx| (SC, 1.211; $P < .01$), and |Dy| (SC, 3.191; $P < .001$), which suggested that the ARR increased in patients who underwent extraction of premolars, as well as in teeth with more horizontal and vertical movement of the incisor tip (Table 5). The ARR of mandibular central incisors correlated with pretreatment tooth length (SC, 1.518; $P < .01$), bracket types (SC, 1.075; $P < .05$), $|\Delta\theta|$ (SC, −1.375; $P < .01$), |Dx| (SC, 1.557; $P < .05$), and |Dy| (SC, 1.332; $P < .001$). This indicated that the ARR increased in teeth that were longer and in those with self-ligating brackets, less change in inclination, and more horizontal and vertical movement of the incisor tip (Table 6).

Risk Factors for ARR With Consideration of ARD

Lastly, multiple linear mixed-model analysis was performed in maxillary and mandibular central incisors, separately, including age, sex, extraction, treatment duration, bracket types, |Da|, |Db|, and Dnet as covariates. The pretreatment tooth length (R1) and $|\Delta\theta|$ were excluded because they were accounted for when calculating |Da| and |Db|. For the maxillary central incisor, ARR correlated only with |Db| (SC, 4.818; $P < .001$). This indicated that the ARR of the maxillary central incisor increased in teeth with greater

Table 3. Apical Root Displacement of Central Incisor (mm)[a]

Characteristic	Conventional Brackets (n = 57), Mean (SD)	Self-Ligating Brackets (n = 78), Mean (SD)	Total (N = 135), Mean (SD)
U1-|Da|	2.53 (1.70)	2.14 (1.54)	2.31 (1.62)
U1-|Db|	1.64 (1.21)	1.74 (1.04)	1.70 (1.11)
L1-|Da|	2.02 (1.20)	2.09 (1.07)	2.06 (1.12)
L1-|Db|	1.62 (1.00)	1.63 (0.90)	1.62 (0.94)
Maxilla (U1)			
Protraction, Da (n = 45)			2.27 (1.74)
Retraction, Da (n = 90)			−2.32 (1.56)
Extrusion, Db (n = 67)			1.78 (1.13)
Intrusion, Db (n = 68)			−1.62 (1.09)
Mandible (L1)			
Protraction, Da (n = 35)			2.00 (1.40)
Retraction, Da (n = 100)			−2.08 (1.02)
Extrusion, Db (n = 53)			1.46 (0.90)
Intrusion, Db (n = 82)			−1.73 (0.96)

[a] SD indicates standard deviation; U1, maxillary central incisor; L1, mandibular central incisor; Da, horizontal apical root displacement; Db, vertical apical root displacement.

Table 4. Risk Factors in All Incisors Without Consideration of Tooth Movement[a]

Independent Variable	ARR, mm Unstandardized Coefficient	95% Confidence Interval	*P* Value
Constant	0.050	(−0.839, 0.893)	.911
Age, y	0.002	(−0.010, 0.013)	.782
Sex (1, male; 0, female)	0.117	(−0.000, 0.233)	.050
Pretreatment tooth length, mm	0.038	(0.004, 0.072)	.027*
Extraction (1, nonextraction; 0, extraction)	−0.153	(−0.265, −0.042)	.008**
Treatment duration, mo	0.004	(−0.001, 0.009)	.127
Bracket type (1, self-ligating; 0, conventional)	0.064	(−0.042, 0.170)	.233
Tooth type[b]			
U1	0.004	(−0.102, 0.111)	.935
U2			
L1	−0.215	(−0.321, −0.108)	<.001***
L2	−0.198	(−0.305, −0.091)	<.001***

[a] ARR indicates apical root resorption; U1, maxillary central incisor; U2, maxillary lateral incisor; L1, mandibular central incisor; L2, mandibular lateral incisor.

[b] Post hoc Bonferroni test: U1, U2 > L1, L2.

* $P < .05$; ** $P < .01$; *** $P < .001$.

Table 5. Risk Factors in Maxillary Central Incisors With Consideration of Crown Movement[a]

Independent Variable	ARR, mm		
	Unstandardized Coefficient (Standardized Coefficient)	95% Confidence Interval	*P* Value
Constant	0.412	(−0.481, 1.305)	.363
Age, y	0.004	(−0.009, 0.017)	.550
Sex (1, male; 0, female)	0.082	(−0.053, 0.217)	.231
Pretreatment tooth length, mm	−0.004	(−0.033, 0.026)	.805
Extraction (1, extraction; 0, nonextraction)	0.175 (1.012)	(0.038, 0.313)	.013*
Treatment duration, mo	−0.000	(−0.000, 0.000)	.859
Bracket type (1, self-ligating; 0, conventional)	−0.082	(−0.203, 0.038)	.179
$\lvert\Delta\theta\rvert$, °	0.021	(−0.012, 0.053)	.210
$\lvert$Dx$\rvert$, mm	0.078 (1.211)	(0.027, 0.130)	.003**
$\lvert$Dy$\rvert$, mm	0.285 (3.191)	(0.218, 0.353)	<.001***

[a] ARR indicates apical root resorption; $\lvert\Delta\theta\rvert$, absolute value of inclination change; $\lvert$Dx$\rvert$, absolute value of horizontal movement of incisor edge; $\lvert$Dy$\rvert$, absolute value of vertical movement of incisor edge.
* $P < .05$; ** $P < .01$; *** $P < .001$.

vertical ARD. Dnet showed a lower SC (3.778; $P <$ .001) than $\lvert$Db$\rvert$, suggesting that ARR of the maxillary incisor correlated more closely with vertical ARD than net movement of the root apex (Table 7). For the mandibular central incisor, ARR correlated with bracket types (SC, 0.941; $P < .05$), $\lvert$Da$\rvert$ (SC, 1.576; $P < .01$), and $\lvert$Db$\rvert$ (SC, 1.807; $P < .001$). Dnet showed a greater SC (2.009; $P < .001$) than $\lvert$Da$\rvert$ and $\lvert$Db$\rvert$ (Table 8). This suggested that ARR of the mandibular incisors increased for teeth with self-ligating brackets and greater ARD in either direction.

DISCUSSION

This study aimed to elucidate risk factors for ARR of maxillary and mandibular incisors by using mathematical quantification of ARD and multiple linear mixed-effects modeling. The results demonstrated that ARD was the strongest contributing factor in ARR. This was supported by the findings that vertical ARD showed the highest SC both in the maxilla and mandible and that horizontal ARD showed the second highest SC in the mandible. These findings contrasted with those of previous studies reporting that ARR of maxillary incisors was marginally significantly correlated only with horizontal ARD.[3–5] This difference may be attributed to the combined effects of the accuracy of ARD measurements and the selection of statistical analyses in the current study. Although Mirabella and Artun[3] mathematically calculated ARD and reported no statistically significant correlation between vertical ARD and ARR, they did caution about the interpretation of their results, because the amount of vertical ARD was less than 1 mm in two-thirds of the patients.

The maxillary and mandibular incisors showed different responses to the direction of ARD. While both vertical and horizontal ARDs correlated significantly with ARR in the mandible, only vertical ARD correlated significantly with ARR in the maxilla. The trabecular bone space is narrower in the mandible; thus, the root movement of the mandibular incisors leads to a higher chance of root contact with cortical bone, which was reported to be a significant risk factor for ARR.[12] In addition, the trabecular thickness of the mandibular anterior region was greater than that of the maxillary

Table 6. Risk Factors in Mandibular Central Incisors With Consideration of Crown Movement[a]

Independent Variable	ARR, mm		
	Unstandardized Coefficient (Standardized Coefficient)	95% Confidence Interval	*P* Value
Constant	−1.189	(−2.398, 0.021)	.054
Age, y)	0.008	(−0.009, 0.026)	.337
Sex (1, male; 0, female)	0.062	(−0.115, 0.240)	.488
Pretreatment tooth length, mm	0.075 (1.518)	(0.029, 0.122)	.002**
Extraction (1, extraction; 0, nonextraction)	−0.145	(−0.375, 0.085)	.214
Treatment duration, mo	0.000	(−0.000, 0.000)	.193
Bracket type (1, self-ligating; 0, conventional)	0.187 (1.075)	(0.027, 0.348)	.022*
$\lvert\Delta\theta\rvert$, °	−0.044 (−1.375)	(−0.077, −0.011)	.009**
$\lvert$Dx$\rvert$, mm	0.097 (1.557)	(0.015, 0.178)	.020*
$\lvert$Dy$\rvert$, mm	0.118 (1.332)	(0.032, 0.203)	.007**

[a] ARR indicates apical root resorption; $\lvert\Delta\theta\rvert$, absolute value of inclination change; $\lvert$Dx$\rvert$, absolute value of horizontal movement of incisor edge; $\lvert$Dy$\rvert$, absolute value of vertical movement of incisor edge.
* $P < .05$; ** $P < .01$; *** $P < .001$.

Table 7. Risk Factors in Maxillary Central Incisors With Consideration of Apical Root Displacement[a]

Independent Variable	ARR, mm Unstandardized Coefficient (Standardized Coefficient)	95% Confidence Interval	*P* Value	Unstandardized Coefficient (Standardized Coefficient)	95% Confidence Interval	*P* Value
Constant	0.312	(0.013, 0.611)	.041*	0.198	(−0.230, 0.626)	.362
Age, y	0.004	(−0.006, 0.013)	.430	0.009	(−0.005, 0.022)	.197
Gender (1, male; 0, female)	0.034	(−0.058, 0.127)	.464	0.102	(−0.031, 0.235)	.131
Extraction (1, extraction; 0, nonextraction)	0.077	(−0.016, 0.171)	.105	0.140 (0.806)	(0.006, 0.273)	.041*
Treatment duration, mo	0.000	(−0.000, 0.000)	.881	0.000	(−0.000, 0.000)	.608
Bracket type (1, self-ligating; 0, conventional)	−0.049	(−0.136, 0.037)	.262	0.024	(−0.099, 0.147)	.698
|Da|, mm	0.004	(−0.025, 0.034)	.765			
|Db|, mm	0.374 (4.818)	(0.330, 0.418)	<.001***			
Dnet, mm				0.191 (3.778)	(0.155, 0.228)	<.001***

[a] ARR indicates apical root resorption; |Da|, absolute value of horizontal apical root displacement; |Db|, absolute value of vertical apical root displacement; Dnet, $\sqrt{Da^2 + Db^2}$.
* $P < .05$; ** $P < .01$; *** $P < .001$.

anterior region[13]; thus, the amount of osteoclastic bone resorption would also be greater in this region, leading to more ARR in response to ARD. Probably due to the anatomical advantage of maxillary alveolar bone, horizontal ARD did not increase the risk of ARR of the maxillary incisors; however, vertical ARD was still the strongest predictor of ARR of the maxillary incisors. Mechanically, with similar force levels, more pressure was concentrated at the root surface during vertical root movement than during horizontal root movement because the area perpendicular to the force is smaller in vertical root movement. Therefore, it can be reasonably speculated that compared with horizontal ARD, vertical ARD has a greater association with ARR.

Premolar extraction has often been reported as a risk factor for ARR of incisors.[4,5] In this study, premolar extraction was significantly correlated with increased ARR when ARD was not taken into account. However, this was not true when the mixed-effects model included horizontal and vertical ARD as covariates. ARD is generally greater in patients who have undergone extraction of premolars, and this was also observed in the subjects of this study, in which vertical ARD was statistically significantly greater in the extraction group (2.02 ± 1.21 mm) than in the nonextraction group (1.44 ± 0.96 mm; $P < .01$).

When ARDs were accounted for in the mixed-effects model, there was another contributing factor for ARR of mandibular incisors: the use of self-ligating brackets. A recent systematic review performed a meta-analysis and concluded no significant difference in ARR between self-ligating and conventional bracket groups.[14] In the studies included in the meta-analysis, however, multiple analysis was not performed, and interactions between various risk factors were not controlled, which can significantly underestimate the impact of self-ligating brackets on ARR. This was also

Table 8. Risk Factors in Mandibular Central Incisors With Consideration of Apical Root Displacement[a]

Independent Variable	ARR, mm Unstandardized Coefficient (Standardized Coefficient)	95% Confidence Interval	*P* Value	Unstandardized Coefficient (Standardized Coefficient)	95% Confidence Interval	*P* Value
Constant	0.195	(−0.396, 0.786)	.515	0.132	(−0.474, 0.738)	.667
Age, y	0.008	(−0.010, 0.026)	.376	0.009	(−0.009, 0.027)	.318
Gender (1, male; 0, female)	0.130	(−0.046, 0.306)	.145	0.134	(−0.042, 0.311)	.135
Extraction (1, extraction; 0, nonextraction)	−0.049	(−0.223, 0.124)	.573	−0.039	(−0.212, 0.135)	.661
Treatment duration, mo	0.000	(−0.000, 0.000)	.173	0.000	(−0.000, 0.000)	.080
Bracket type (1, self-ligating; 0, conventional)	0.164 (0.941)	(0.002, 0.326)	.048*	0.177 (1.018)	(0.014, 0.340)	.033*
|Da|, mm	0.121 (1.576)	(0.049, 0.193)	.001**			
|Db|, mm	0.166 (1.807)	(0.077, 0.255)	<.001***			
Dnet, mm				0.176 (2.009)	(0.094, 0.255)	<.001***

[a] ARR indicates apical root resorption; |Da|, absolute value of horizontal apical root displacement; |Db|, absolute value of vertical apical root displacement; Dnet, $\sqrt{Da^2 + Db^2}$.
* $P < .05$; ** $P < .01$; *** $P < .001$.

observed in this study in that L1 ARR was not statistically significantly different between the two bracket groups when multiple analysis was not performed (Table 2). One possible explanation for the association of self-ligating brackets with ARR is that higher buccolingual forces were generated in crowded mandibular incisors by self-ligating brackets than conventional brackets.[15] It has regularly been reported that increased force level is positively correlated with increased ARR.[16]

There were some limitations to this study. First, this was a retrospective study, which may be subject to some biases. Although the subjects were randomly selected from the pool of patients, there still might have been a selection bias that occurred during the treatment-planning step, such as the decision for extraction or selection of the bracket type. Second, two-dimensional images used in this study have inherent sources of errors. Recently, three-dimensional (3D) cone-beam computed tomography (CBCT) has been successfully used to evaluate ARR in 3D space.[17] Future studies using 3D CBCT may demonstrate more direct associations between ARR and ARD.

CONCLUSIONS

- Mathematical calculation of ARD combined with linear mixed-effects model analysis revealed that ARD was the strongest contributing factor for ARR after orthodontic treatment.
- While vertical ARD was a critical factor for ARR of both maxillary and mandibular incisors, horizontal ARD was significantly correlated only with ARR of mandibular incisors.
- Careful monitoring of ARR is recommended in patients requiring significant ARD of incisors.

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