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Original Article

Root Growth and Apical Foramen Closure Velocity of Maxillary Permanent Central Incisor in Korean Children

Sung-Joo Kim, Hyuntae Kim, Ji-Soo Song, Teo Jeon Shin, Young-Jae Kim, Jung-Wook Kim, Ki-Taeg Jang, Hong-Keun Hyun
Department of Pediatric Dentistry, Dental Research Institute, School of Dentistry, Seoul National University, Seoul, Republic of Korea

Abstract

This study aimed to evaluate the growth velocity of root elongation and the timing of apical foramen closure in maxillary permanent central incisors using panoramic radiographs. The study also examined the timing of alveolar eruption and its relationship with root development while considering potential sex-specific differences. The study included 176 patients (94 males, 82 females) from the Seoul National University Dental Hospital, each with three or more panoramic radiographs taken between 2014 and 2023 and analyzed to measure the crown length, total tooth length, root length, and mesiodistal width of the apical foramen. Root lengths were expressed as percentages of the fully developed stage. Scatter plots and polynomial trend lines were used to evaluate the relationship between age and tooth development, with intraobserver reliability assessed using Cohen's kappa. Root growth velocity peaked during the early stages of development, with females generally exhibiting earlier and faster apical foramen closure than males. Significant correlations were found between the root length and apical foramen width (Pearson correlation coefficients, males, -0.907; females, -0.887, $p < 0.0001$). The mean age for alveolar eruption was 7.27 years for males (N = 16) and 7.10 for females (N = 17), predominantly at Demirjian stage F. The study presents the critical periods of rapid root elongation and apical foramen closure in the maxillary central incisors, underscoring their importance for clinical dental practice. Future research is warranted to provide a more comprehensive understanding of human dental development. [J Korean Acad Pediatr Dent 2024;51(4):432-441]

Keywords

Maxillary central incisors, Root growth, Apical foramen closure, Panoramic radiography, Dental development

ORCID
Sung-Joo Kim
https://orcid.org/0009-0001-8526-0332
Hyuntae Kim
https://orcid.org/0000-0003-2915-8584
Ji-Soo Song
https://orcid.org/0000-0002-4469-5903
Teo Jeon Shin
https://orcid.org/0000-0003-4499-8813
Young-Jae Kim
https://orcid.org/0000-0003-4916-6223
Jung-Wook Kim
https://orcid.org/0000-0002-9399-2197
Ki-Taeg Jang
https://orcid.org/0000-0002-4060-9713
Hong-Keun Hyun
https://orcid.org/0000-0003-3478-3210

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Corresponding author: Hong-Keun Hyun
Department of Pediatric Dentistry, Dental Research Institute, School of Dentistry, Seoul National University, 101 Daehak-ro, Jongno-gu, Seoul, 03080, Republic of Korea
Tel: +82-2-6256-3262 / Fax: +82-2-6256-3266 / E-mail: hege1@snu.ac.kr

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Introduction

An immature permanent tooth can be defined as a newly erupted permanent tooth with incomplete root apex formation. Once erupted, root development and apical closure take approximately 3 years[1]. Root development involves interactions between the dental follicle, epithelial root sheath of Hertwig, and dental papilla. Hertwig's epithelial root sheath is responsible for the future shape of the roots[2].

Despite studies on dental eruption timing for children worldwide[3-5], fewer studies have examined dental development as a process extending across years or decades. The existing literature primarily focuses on the mandibular teeth[6-9]. In addition, while Moorrees et al.[10], Haavikko[11], and Liversidge[12] have published papers on tooth formation, their data are quite outdated. Among the early staging techniques, the method by Demirjian et al. is still widely used[13]. Many researchers have applied Demirjian's technique to children of different countries[14,15]; however, few studies have examined tooth root development beyond its use in obtaining dental age.

Despite its importance, research on root development and apical foramen of permanent maxillary central incisors is limited. These incisors, which are located prominently at the center of the face, typically erupt between the ages of 7 and 8 years during the transition from deciduous to mixed dentition[3]. Immature teeth are susceptible to pulp involvement because of factors such as trauma, caries, or iatrogenic causes. Dental trauma is a prevalent reason for children with immature permanent teeth to undergo root canal treatment or pulpal therapy, affecting approximately 20% of children and adolescents with permanent dentition[16]. Studies have indicated that 13.5% of children experience traumatic injuries to their permanent teeth before the age of 12[17]. Among these, the maxillary central incisors are most frequently affected.

These teeth must be preserved to ensure their long-term retention. The appropriate type of pulp therapy is determined by whether the pulp is vital or nonvital. After diagnosis, several treatment options are available for vital teeth, including pulp capping and pulpotomies. These treatments aim to preserve the health of the root pulp, support spontaneous pulp growth, and require continuous monitoring until root formation is complete. The speed of root growth and apical foramen closure rate are vital in determining treatment duration[18]. However, current research lacks comprehensive data on these parameters for maxillary central incisors. The duration of root growth, periods of rapid root elongation, timing of apical foramen closure, and degree of apical closure required for effective endodontic treatment are less understood.

This study aimed to evaluate the growth velocity of root elongation and the timing of apical foramen closure in maxillary permanent central incisors by analyzing a series of panoramic radiographs from a cohort of Korean children, measuring root length and apical foramen width over time. Specifically, the focus is on the development of maxillary central incisors, given their critical role in early dental development and treatment, particularly in cases of trauma or other dental issues. Because panoramic radiographs are essential in dental examinations, they can be incredibly useful for assessing the developmental progress of permanent teeth. Ultimately, the timing of the eruption of these teeth may be predicted with greater precision, an ability that would have important clinical implications[19]. A better understanding of the variability in dental growth and development would provide greater insights into human adaptation and evolution of hominid growth and development[20,21]. Studies of human dental development, in addition to their clinical utility, contribute significantly to this theoretical enterprise. As our predictive ability improves, so does our ability to understand previous developmental patterns.

Materials and Methods

1. Data collection and sampling

This study included 176 Korean children (94 males and 82 females) who visited the Seoul National University Dental Hospital between 2022 and 2023. These patients had final radiographs showing apical closure and complete root development of the maxillary permanent central incisors and had three or more consecutive panoramic radiographs taken between 2014 and 2023. In total, 732 radiographs were selected (383 and 349 from male and female patients, respectively). To minimize overlap errors, all panoramic radiographs were taken using the same panoramic radiograph machine Orthopantomograph® (Instrumentarium Dental, Tuusula, Finland). The study protocol was approved by the Institutional Review Board of the School of Dentistry at Seoul National University (IRB No. ER124020).

Patients who had poor - quality radiographs, a history of orthodontic treatment, or systemic conditions such as Down syndrome, cleft lip and palate, or other systemic diseases were excluded. Patients with maxillary anterior jaw lesions, eruption disturbances or congenital absence of maxillary central incisors, history of invasive surgery in the anterior region (e.g., removal of supernumerary teeth), trauma history to the maxillary primary or permanent central incisors, or history of endodontic treatment of the maxillary central incisors were also excluded.

Data were collected from participants' records, including sex, age, birth year, and timing of panoramic radiographs. The intervals between panoramic radiographs varied from 1 to 48 months, and the follow-up duration ranged from 4 to 84 months. Using the ImageJ (National Institutes of Health, USA) and integrating the Turboreg plugin, based on three points on the crown of the maxillary right central incisor, earlier panoramic radiographs were superimposed on the most recent radiograph to minimize angular distortion. Measurements included crown length (from the midpoint of the incisal edge to the midpoint of the cementoenamel junction [CEJ] line), total tooth length (from the midpoint of the incisal edge to the midpoint of the root apex), apical foramen's mesiodistal width (distance between the growth termini of the root apex), and the tooth developmental staging system suggested by Demirjian et al.[13]. The root length was calculated by subtracting the crown length from the total tooth length. The root length from the fully developed stage was set at 100%, and root lengths from earlier radiographs were presented as percentages of this length.

Panoramic radiographs were selected to reveal alveolar eruption of the permanent maxillary central incisors. Out of the total 732 selected panoramic radiographs, 33 images showing the alveolar eruption of the maxillary central incisors were selected. Alveolar eruption was determined when the incisal edge of the permanent maxillary central incisor was positioned above the CEJ line of the preceding primary maxillary central incisor or on the line connecting the CEJ line of the fully erupted adjacent teeth.

2. Data analysis

Demographic data were analyzed using SPSS software version 21.0 (SPSS Corp., Armonk, NY, USA). Scatter plots of the percentage of the root growth of maxillary central incisors versus the child's age in months with separate and combined sex models were created, excluding radiographs taken after the root had reached 100% formation and apical foramen closure (Demirjian stage H). This exclusion prevented the dataset from skewing toward fully mature dentitions. Films of dentitions nearing maturity were analyzed. Scatter plots represented changes in the root length and apical foramen diameter, with separate and combined sex models because of evident sex differences. Trend lines with higher R-squared values were used for interpretation. The left and right teeth were included in the analysis without distinction. The correlation between the root length and apical foramen width was analyzed using Pearson's correlation. Intraobserver reliability was assessed using Cohen's kappa, analyzing a sample of 100 radiographs.

From the 33 selected images showing the eruption of the maxillary central incisors out of the total panoramic radiographs, the patient's age, root length, apical foramen width, and percentage of the final root length were analyzed by sex for means and standard deviations. A frequency analysis of the Demirjian stage of the teeth in the selected images was conducted.

Results

1. Intraobserver agreement

Cohen's weighted kappa values of the intraobserver agreement for root length, apical foramen width, and dental developmental stages were 0.94, 0.93, and 0.98, respectively ($p < 0.0001$).

2. Study cohort demographics

Table 1 presents the descriptive statistics of the study cohort. From a pool of 13737 patients who underwent diagnostic panoramic radiography at the Pediatric Dentistry Department of Seoul National University Dental Hospital between January 2022 and December 2023, a final cohort of 176 patients meeting the research criteria was included in the study (Fig. 1, flow chart of the study population selection). This comprised 94 males (53.4%) and 82 females (46.6%), with an average age of 11.05 ± 0.63 (range, 9.67 - 13.06) years, at the time the final panoramic radiographs were taken, showing complete root formation and apical foramen closure. The number of panoramic radiographs per patient varied from 3 to 8. The number of patients per number of panoramic radiographs is summarized in Table 1. The most common number of radiographs taken was 4, with 80 of the 176 patients having four sets. The average total follow-up period per patient was 45.38 ± 17.734 (range, 4 - 84) months.

Table 1. Demographic data of the study

Age of the Most Recent Panoramic Radiograph Per Patient		Mean ± SD
	Total (year)	11.05 ± 0.63
	Range (year)	n
	9.5 - 10.0	2
	10.0 - 10.5	41
	10.5 - 11.0	39
	11.0 - 11.5	46
	11.5 - 12.0	42
	12.0 - 12.5	5
	12.5 - 13.0	1
Gender		n (%)
	Male	94 (53.4)
	Female	82 (46.6)
Number of Radiographs	n Per 1 Patient	n
	3	48
	4	80
	5	30
	6	11
	7	4
	8	3
	Total	732
Total Follow-up Duration		Month
	Mean ± SD	45.38 ± 17.73
	Minimum	4
	Maximum	84
Intervals Between Panoramic Radiographs		
	Minimum	1
	Maximum	48

n: number.

3. Correlation between root length and apical foramen width

Pearson correlation analysis showed that the percentage of the root length and diameter of the apical foramen had a correlation of -0.907 in males and -0.887 in females, with a significance level of $p < 0.0001$ for both sexes.

4. Time-dependent root length and apical foramen diameter with trend line equations

The time-dependent root lengths and time-dependent apical foramen diameters of the maxillary central incisors are shown in Fig. 2 and Fig. 3, respectively. A trend line for polynomials of a higher order was plotted on each graph.

In the combined sample of males and females, the trend line graph showed accelerated root length growth at the age of 5.77 years, and the root was 30.8% complete at this point. The root length growth rate started to decline at the age of 8.07 years, and the root was 76.3% complete at that point. The duration of the growth spurt was 2.52 years. The apical foramen width started to accelerate at the age of 5.74 years, when the width was 5.09 mm in the combined sample. The velocity started to decrease at 8.83 years, and the apical foramen width

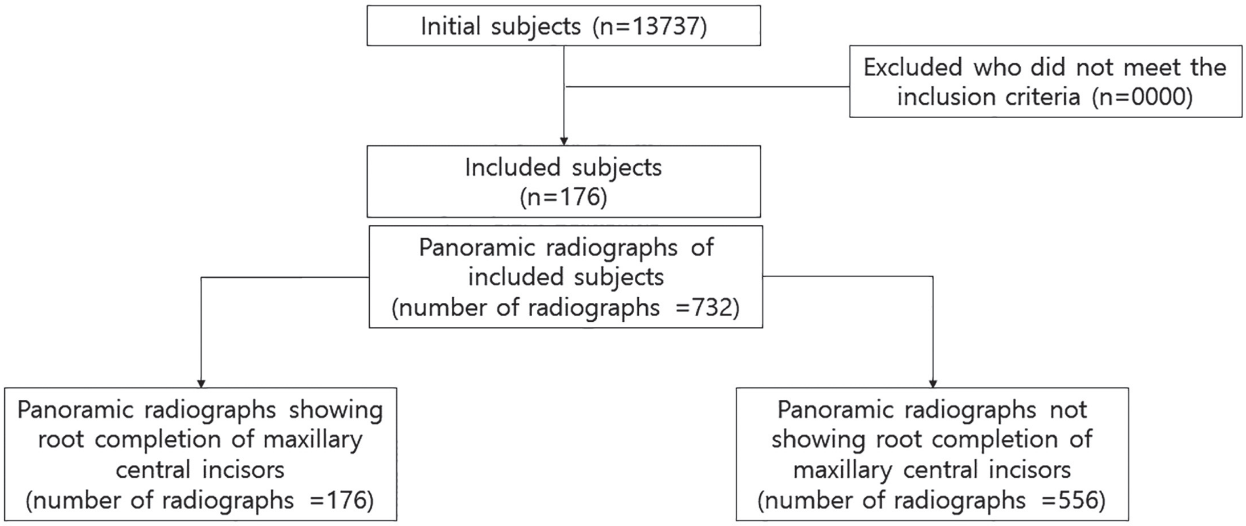

Fig. 1. Flow chart of participant selection in this study.

was 1.25 mm at this point. The duration was 3.08 years, which was longer than that of the root length growth.

The trend line equations were calculated as follows:

- Root length of the maxillary central incisors in males = $-0.036x^6 + 1.7745x^5 - 35.625x^4 + 371.31x^3 - 2114.1x^2 + 6237.5x - 7440.3$
  $r^2 = 0.753$
- Root length of the maxillary central incisors in females $= -0.0189x^6 + 0.905x^5 - 17.56x^4 + 176.46x^3 - 966.08x^2 + 2745.3x - 3169.9$
  $r^2 = 0.7933$
- Root length of the maxillary central incisors in the combined cohort = $-0.0246x^6 + 1.2069x^5 - 24.049x^4 + 248.42x^3 - 1399.7x^2 + 4088.8x - 4836.9$
  $r^2 = 0.7703$
- Apical foramen diameter of the maxillary central incisor in males = $0.0009x^6 - 0.0452x^5 + 0.9161x^4 - 9.5598x^3 + 53.841x^2 - 155.34x + 185.46$
  $r^2 = 0.7563$
- Apical foramen diameter of the maxillary central incisor in females = $0.0001x^6 - 0.0061x^5 + 0.1004x^4 - 0.6897x^3 + 1.1522x^2 + 5.7663x - 11.272$
  $r^2 = 0.8021$
- Apical foramen diameter of the maxillary central incisor in the combined cohort = $0.0003x^6 - 0.0156x^5 + 0.3033x^4 - 2.9587x^3 + 14.941x^2 - 37.053x + 41.321$
  $r^2 = 0.7798$

In the equations, x is the age in years.

The R-squared (r^2) value was > 0.6, indicating a significant correlation.

5. Alveolar eruption and demirjian stage

In the panoramic radiographs, alveolar eruption of maxillary central incisors was observed in 33 images, involving 16 male and 17 female patients. The mean age at the time of eruption was 7.27 ± 0.74 years for men and 7.10 ± 0.56 years for women, with an overall mean age of 7.18 ± 0.65 years. The results for each sex, *p*-value for differences between sexes, and combined results for both sexes are presented in Table 2.

The root length, apical foramen width, and percentage of the root length also tended to show earlier development in females than in males; however, the p-values for the differences between sexes were all > 0.05, indicating no significant differences. At the time of alveolar eruption for the maxillary incisors, the Demirjian stage was predominantly stage F, observed in 28 out of 33 images (84.8%). This was followed by stage E in 4 images (12.1%) and stage G in 1 (3%).

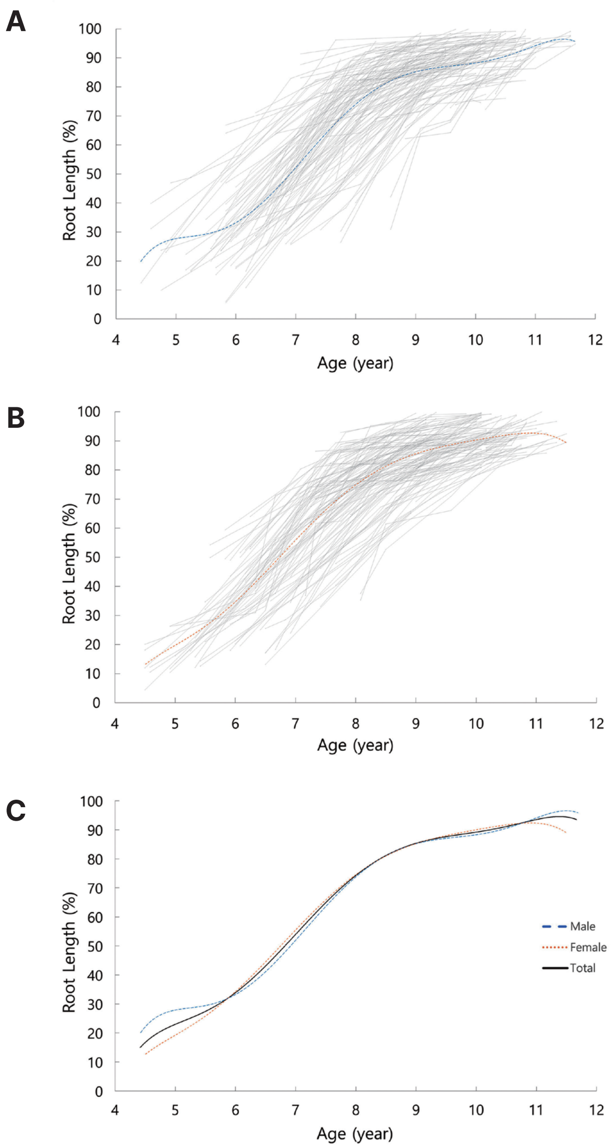

Fig. 2. Increase in root length (%) according to age in (A) males, (B) females, and (C) combined. The gray line segments represent the values for each patient, whereas the curve running through the middle represents the trend line in (A) and (B). (C) Trend lines for both females and males as well as combined data from both sexes, all in a single figure.

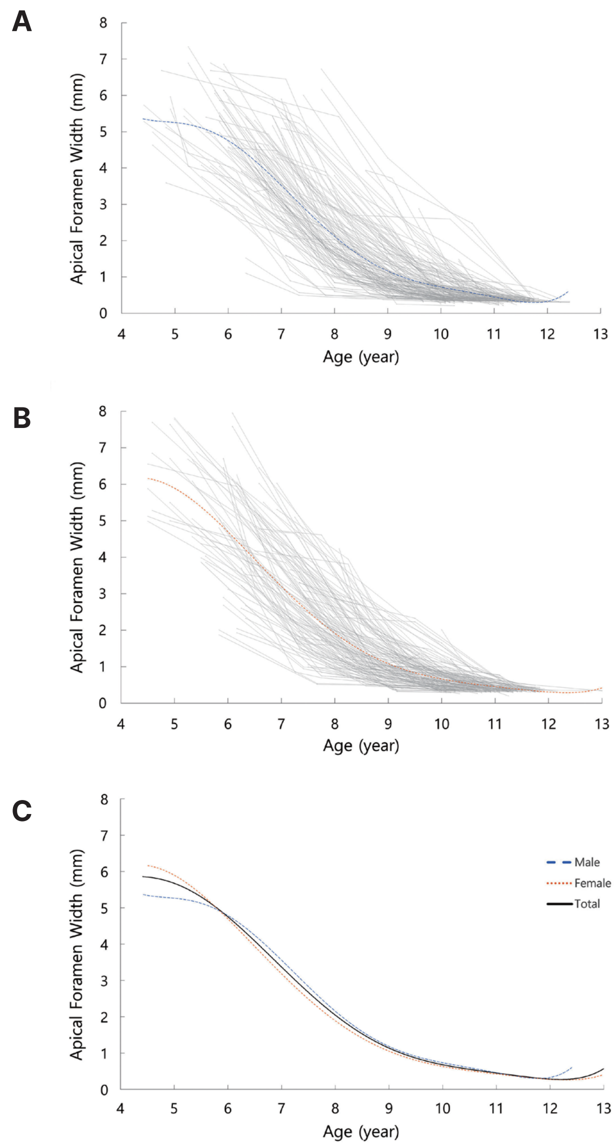

Fig. 3. Apical foramen width (mm) according to age in (A) males, (B) females, and (C) combined. The gray line segments represent the values for each patient, whereas the curve running through the middle represents the trend line in (A) and (B). (C) Trend lines for females, males, and combined data from both sexes, all in a single figure.

Table 2. Statistics of panoramic radiographs showing alveolar eruption of maxillary central incisors in men, women, and total

	Male (n = 16)		Female (n = 17)			Total (n = 33)	
	Mean	SD	Mean	SD	*p*	Mean	SD
Age (year)	7.27	0.74	7.10	0.56	0.447	7.18	0.65
Width of Apical Foramen (mm)	3.92	0.85	3.46	1.08	0.192	3.68	0.99
Length of root (mm)	9.30	2.09	9.44	2.29	0.850	9.37	2.16
Percentage of Root Growth (%)	49.37	9.46	52.64	11.94	0.393	51.06	10.77

The difference between men and women was analyzed by the independent *t*-test.
n: number of patients.

Discussion

For theoretical and practical reasons, gaining a more nuanced understanding of dental maturation is essential[15,20]. Comprehensive datasets from large longitudinal studies conducted in the mid-20th century remain invaluable, and smaller-scale studies focusing on contemporary pediatric populations are crucial for addressing specific questions and providing updates that account for potential secular trends. These studies also help in examining regional variations in dental maturation.

In the present study, the percentage curves generated from the age in months (Fig. 2 and Fig. 3) exhibit a simple pattern of root elongation through time, relative to the total tooth length, for the maxillary central incisors between the ages of 4 and 13. Because for the ages surveyed the crowns of these teeth have completed formation and thus should have a stable length, the pattern displayed implies the velocity of the root growth over this age span, which increases until the peak velocity, and decreases afterward. In the study of Moorrees et al.[10], root formation, again expressed as a mean time interval from crown formation to root complete, occurred in 3.3 years for the maxillary central incisors. The root complete was around the average age of 8.5 years, with 2 standard deviations at approximately 7.7 - 11.17 years[10]. In the present study, the average age of the last panoramic radiograph was 11.05 years, which is approximately 3 years later than the result by Moorrees et al.[10]. For accurate interpretation and application, terminologies should not be different between the two studies. In the study by Moorrees et al.[10], the term “root complete” was defined as “root length complete,” indicating the full-length extension of the root. After “root complete,” a distinct term of “apex closed” refers to the apex closure of the root. However, in the present study, age data of “apex closed” was only collected; thus, a precise comparison cannot be made between the results of the two studies. However, the age in the present study is also not the average age of apical closure because it is the point when the apical closure has already happened, not the exact point of apical closure; thus, in reality, the age at apical closure must be earlier than 11.05 years. To compare with the results of Logan and Kronfeld[1], the age of enamel formation completion of the maxillary central incisors is 4 - 5 years, and the age of eruption is 7 - 8 years. The age of complete root formation and apical foramen closure is reported as 10 years, which is pretty much consistent with the results of the present study because the age at alveolar eruption was 7.18 $\pm$ 0.65 years, and the age at complete root formation and apical foramen closure was expected to be slightly earlier than 11.05 years. Haavikko[11] reported the median of 9.3 years as the age for apical closure for the maxillary central incisors for females and 9.8-year age for males. This was also earlier than the mean age calculated from the present study.

Moorrees et al.[10] implied that root growth velocity progressively increased from root one - quarter to root complete. The present results are more consistent with those of Haavikko[11]. She proposed a pattern similar to that found in the present study, that is, that tooth roots had growth spurts, usually between root one-half and root complete; for incisors and canines, the spurt was suggested to occur earlier, in the middle two-quarters of root development. The “spurt” for the maxillary central incisors for females was at about the root one-quarter.

The present study indicated the equation of the trend line of the root length and apical foramen width in both sexes. By substituting the age in months into the equation representing the trend line, the root length or apical foramen size can be calculated. Conversely, by entering the desired root length or apical foramen size into the equation, the corresponding age in months at which that length or width occurs can be determined.

Typically, females are more advanced in their relative root growth timing than males. Although the root growth timing was earlier in females than males in their ages, this study also showed that the maximum root growth rate, which is the slope of the trend line of the graph in Fig. 3, was faster in males than in females. Males tended to show faster root growth at the growth spurt and tended to prolong the growth until later than females. Nevertheless, the timing and rate of apical foramen closure appeared to be faster in females. The timing of alveolar eruption also showed sex difference, and females tended to show earlier eruption than males, although the difference was not significant. These findings are consistent with those presented by Demirjian et al.[13], indicating that overall tooth growth timing is generally more advanced in females than in males[19].

Because other previous studies lack data on the root development of maxillary central incisors, direct comparisons with previous studies are difficult. However, because several studies were performed with other teeth, it could be compared if some similarities or differences were present between these teeth. Smith and Buschang[7] examined the tooth root development of mandibular canines and premolars on an orthodontic sample. The study examined the velocity at milestones of root one-half and root three-quarters. At root one-half for the mandibular canine root growth, the velocity slightly increased. The velocity was nearly stable at root three-quarters but was past the peak velocity. For the mandibular first premolar, velocity was around the minimum at root one-half and was nearing peak velocity at root three-quarters. For mandibular second premolars, velocity was already increasing at root one-half and was near the peak velocity at root three-quarters. In the present study, at approximately root one-quarter, the velocity started to increase. Root one-half was around the peak velocity of root growth. From the point around root three-quarters, the graph started to show a plateau, which means that the root growth was nearly completed. Liversidge et al.[15] reported mean ages for stage H (apex complete) were 7.90 $\pm$ 0.11 years for females and 8.34 $\pm$ 0.11 years for males for the mandibular central incisors. Because the study of Liversidge et al.[15] and the present study both used intermittent data, which is the radiograph of certain timing, it is not accurately the timing of the apex complete.

According to Simpson and Kunos[8], the rate of morphological change of the mandibular central incisors increases after the root is approximately 15% complete. The rate of root elongation remains high until approximately 90% of the root is completed. As expected, the rate of root elongation is the greatest in the period accompanying emergence[22]. This pattern is slightly different from that in our study, in which at 30.8% of root completion, the root length velocity started to accelerate. After 85% - 90%, the graph tended to show a plateau. Similarly, while Simpson and Kunos[8] found the mandibular central incisors to reach their full lengths between 7 - 8 and 1/4 years, our sample shows some continued slow growth beyond these ages, particularly for males. Although the general pattern showed similarity, this might be the difference between the pattern of maxillary and mandibular incisors. Maxillary central incisors tended to accelerate later than the mandibular central incisors in their root length growth.

Studies have compared modern humans with past ancestors. Dean and Vesey[23] found a clearer pattern of the peak extension rates for the posterior teeth (molars) than for the anterior teeth (incisors and canines). In the study by Dean and Vesey[23], as part of anthropological research, the root growth rates at the time of eruption in modern humans and great apes were compared through histological analysis. This study used the circadian incremental markings in dentin. De Castro et al.[20] compared the perikymata of Homo sapiens and Homo heidelbergensis to investigate crown formation rates. This study demonstrated that ancient hominins completed crown formation at a shorter time than modern humans.

Previous studies have also investigated the relationship between the timing of eruption and root growth. In the study of Feasby[9], the root growth rates of mandibular canines to second molars were measured using lateral cephalograms. Eruption rates were also measured using the inclination from the mandibular inferior border to examine its correlation with root length. Of particular interest was the low correlation between the maximum eruption rate and increments in root growth. This finding indicates that the eruption surge and root increments were independent variables. In addition, when the mean maximum eruption rates were compared with the mean root growth during the eruption, the eruption exceeded root growth by as much as 4.6 mm. These circumstances indicate that the most dramatic phase of the eruption could not be accounted for by root growth alone. In comparison, the present study measured the root length and age at the time of eruption; however, the eruption rate was not of interest. This can be investigated in further studies, and as the previous studies have suggested the line of the mandibular inferior border as the criteria to measure the eruption of mandibular teeth, a new line of criteria for the maxillary teeth must be presented.

When measuring the Demirjian stage and eruption, stage F was the most significant eruption, followed by stages E and G. Demirjian stage F occurs when the walls of the pulp chamber form an isosceles triangle. The apex ends in a funnel shape. The root length is equal to or greater than the crown height[13]. When stage G is past and if the maxillary central incisor is still not erupted, then proactive treatment for eruption management should be needed. Given that Demirjian's technique has been shown to have varying accuracy across ethnicities, the findings in this study of Korean children should be considered within the context of ethnic differences in dental development[24]. According to the study done by Jeong et al.[25], both the root length and tooth volume of the maxillary incisors with eruption disturbances were significantly smaller than those of normally erupting incisors. This suggests that eruption disturbances may influence tooth development, underscoring the need for appropriate interventions.

This study found a high correlation between root length and apical foramen width. Both the elongation of the root and constriction of the apical foramen would be naturally associated because they are both growth processes. Thus, if the constriction of the apical foramen has already occurred in teeth with shorter than normal root lengths, further root growth may be difficult to expect.

The limitations of this study include the potential distortion from using panoramic radiographs to measure the root length and apical foramen width, and only the mesiodistal width of the apical foramen was measured. The panoramic radiographs were also not taken at consistent intervals. Future studies conducted on various teeth could provide more valuable information regarding human dental development.

Conclusion

This study provides information on the developmental patterns of root growth and apical foramen closure in maxillary permanent central incisors. The findings reveal the critical periods of rapid root elongation and apical foramen closure, which are essential to understanding the timing and management of dental treatments, particularly in pediatric patients. While the results suggest that females generally tend to experience earlier and faster apical foramen closure than males, this observation reflects a trend rather than a statistically significant difference. Additionally, significant correlations were found between root length and apical foramen width across both sexes. Further studies using a similar methodology could explore maxillary lateral incisors, canines, and premolars to offer additional insights into the developmental patterns of these teeth.

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Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

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