BMC Oral Health

RESEARCH Open Access

Three-dimensional partitioning and quantification of orthodontic root resorption via automatic root extraction from cone-beam computed tomography

Jing Huang[1,2], Mengjie Wang[1,2], Xuan Tang[1,2], Leilei Zheng[1,2,3] and Chongshi Yang[1,2,3,4*]

Abstract

Background External root resorption (ERR) during orthodontic treatment is a common concern, and accurate quantification is crucial for assessing outcomes and minimizing long-term complications. This study aims to quantify ERR using automated root extraction from cone beam computed tomography (CBCT), combined with a novel root partitioning method and enhanced through the integration of intraoral scans for improved accuracy.

Methods Thirty-six patients with malocclusion were included and divided into two groups. Root extraction was performed on CBCT images using artificial intelligence (AI), Simultaneously, crown data from intraoral scans were integrated to create composite dental models in Geomagic software. Pre- and post-treatment models were aligned based on crowns. A novel partitioning method was then used to analyze root volume changes in three dimensions. Finally, these changes were analyzed according to age, tooth region, and extraction treatment using SPSS software.

Results A statistically significant reduction in root volume was observed post-treatment in both groups ($P < 0.001$). Anterior teeth exhibited greater ERR, especially in the upper anterior teeth of Group II (extraction treatment, $P < 0.05$). Posterior maxillary teeth in Group I showed less ERR ($P < 0.05$). ERR was more pronounced in the apical third of the root ($P < 0.001$). Group II experienced greater overall ERR, particularly in the apical third, whereas Group I showed more ERR at the cervical third ($P < 0.05$).

Conclusion This 3D quantification method provides a novel assessment of ERR, with distribution influenced by age, tooth position, extraction treatment, and root region.

Keywords Automatic root extraction, Cone-beam computed tomography, External root resorption, Quantitation, Three-dimensional imaging

*Correspondence:
Chongshi Yang
500262@cqmu.edu.cn
[1]College of Stomatology, Chongqing Medical University, Chongqing, China
[2]Department of Orthodontics, College of Stomatology, Chongqing Medical University, Chongqing, China
[3]Chongqing Key Laboratory of Oral Diseases and Biomedical Sciences, Chongqing, China
[4]Department of Orthodontics, Chongqing Key Laboratory of Oral Diseases and Biomedical Sciences, Stomatological Hospital of Chongqing Medical University, #426 Songshi North Road, Chongqing 401147, China

Introduction

External root resorption (ERR) is a common complication of orthodontic treatment [1–3], which can lead to tooth mobility and, in severe cases, premature tooth loss, ultimately affecting the long-term viability of the dentition. Unfortunately, ERR is almost inevitable in orthodontic practice, with prevalence rates ranging from 20 to 100% [4, 5].

The variation in ERR prevalence across studies can be attributed to differences in the criteria used for assessment and detection. While histologic examination is considered the gold standard, its use is limited in orthodontic clinics. As a result, imaging techniques are the primary method used for detecting ERR [6].

Two-dimensional (2D) X-ray imaging, such as apical, panoramic, and lateral cephalometric radiographs, has traditionally been used to detect ERR [7, 8]. However, the accuracy and precision of ERR detection can be compromised by image distortion, superimposition of anatomical structures, and the projection angle [9].

Cone Beam Computed Tomography (CBCT) overcomes the limitations of 2D imaging by providing three-dimensional (3D) data without magnification errors, using a 1:1 scale reconstruction [5, 9, 10]. It enables multiplanar viewing and allows for both 2D linear or angular measurements [11, 12], and 3D volumetric measurements to detect ERR [13–15]. Given the multi-directional movement of teeth during orthodontic treatment [16]. ERR can occur on any side of the tooth root, exhibiting various sizes and shapes. Consequently, 2D analyses, such as ERR length measurements, may not be sufficient, while 3D volumetric measurements offer a more accurate and comprehensive assessment of ERR [17].

For 3D volumetric measurements, the extraction of the root from CBCT data is a critical step. Previous studies, manual thresholding was used to segment the tooth from adjacent teeth and the alveolar bone [18–20], however, this method was time-consuming and labor-intensive. Furthermore, accuracy and precision were also common issues with this approach [21]. Artificial intelligence (AI) technology offers an ideal solution by automating the extraction of the tooth from surrounding structures [22].

The consistency of the detection site before and after orthodontic treatment is another important factor in detecting ERR [23–25]. Due to the limitations of CBCT resolution, which can result in a lack of well-characterized structures, the accuracy of registration can be compromised, thereby reducing the reliability of the results. This limitation can be overcome by combining intraoral scanning, which generates precise images of the crowns. A composite tooth model with accurate crown features and 3D root morphology can be created by integrating the complementary advantages of these two 3D imaging techniques.

Given the limitations associated with traditional measurements, a new approach for 3D quantification of ERR during orthodontic treatment was needed. Therefore, the aim of this study was to develop a novel method for quantifying partitioned root volume through the 3D registration of a composite tooth model created from intraoral scans and CBCT data. Additionally, the study aimed to evaluate the impact of orthodontic treatment on ERR at different ages and tooth positions using this new method.

Methods

This retrospective study was approved by the Ethics Committee of the Stomatological Hospital of XXX Medical University (Approval No. XXX). Based on the pre-experiment ERR (mean 17.41, standard deviation 35.46), calculated using PASS software (version 15.0; NCSS Statistical Software, Kaysville, Utah), and assuming a power of 80% and an alpha value of 0.05, a minimum sample size of 35 patients was required for the study, using the two-sided Wilcoxon test.

A total of 36 subjects were included based on the following criteria: ① patients who had completed orthodontic treatment at the orthodontic department of the Stomatological Hospital; and ②patients with intact dental crowns throughout orthodontic treatment, without significant morphological changes, such as large resin fillings or dental prostheses.

The patients were divided into two groups based on age [26]. Group I consisted of 18 patients (aged 10–15 years) with a total of 459 teeth, including 213 anterior teeth (106 maxillary [72 in extraction cases and 34 in non-extraction cases] and 107 mandibular). The remaining 246 were posterior teeth, with 120 in the maxilla and 126 in the mandible. Group II included 18 patients (aged ≥ 15 years) with a total of 456 teeth, comprising 212 anterior teeth (106 maxillary [54 in extraction cases and 52 in non-extraction cases] and 106 mandibular) and 244 posterior teeth (116 maxillary and 128 mandibular).

CBCT and intraoral scans were collected before treatment (T0) and after treatment (T1). An intraoral scanner (iTero Element; Align Technology, Santa Clara, CA, USA) was used to capture the surface morphology of the dentition. All CBCT images were obtained with the KaVo Dental Excellence (KaVo 3D exam; KaVo Dental, Biberach, Germany) at the Stomatology Hospital. The radiological parameters were set as follows: 120 kVp, 5 mA; voxel size: 0.4 mm; exposure time: 8.9 s; and a field of view: 16 × 17 cm.

Root volume measurement was performed in three steps: first, the construction of composite dental models; second, the alignment of individual composite teeth at T0 and T1; and third, the segmentation and partitioning of the root, followed by volume computation.

Construction of dental composite models

Teeth were extracted from CBCT images using an AI algorithm [22], and exported in STL format. Composite tooth models were generated by aligning and merging the dentition from the CBCT and the intraoral scan based on crown morphology, using a computerized algorithm [27]. The final composite models were then imported into Geomagic Wrap software (version 2017; Geomagic, Morrisville, NC, USA) for segmentation into individual teeth (Fig. 1).

Alignment of individual composite tooth before treatment and after treatment

To ensure consistent partitioning of the root before and after orthodontic treatment, the tooth models were registered. The crown was used as a reference for registering the tooth models at T0 and T1 using a 1-point registration method in Geomagic software (Geomagic, Morrisville, NC, USA) (Fig. 2).

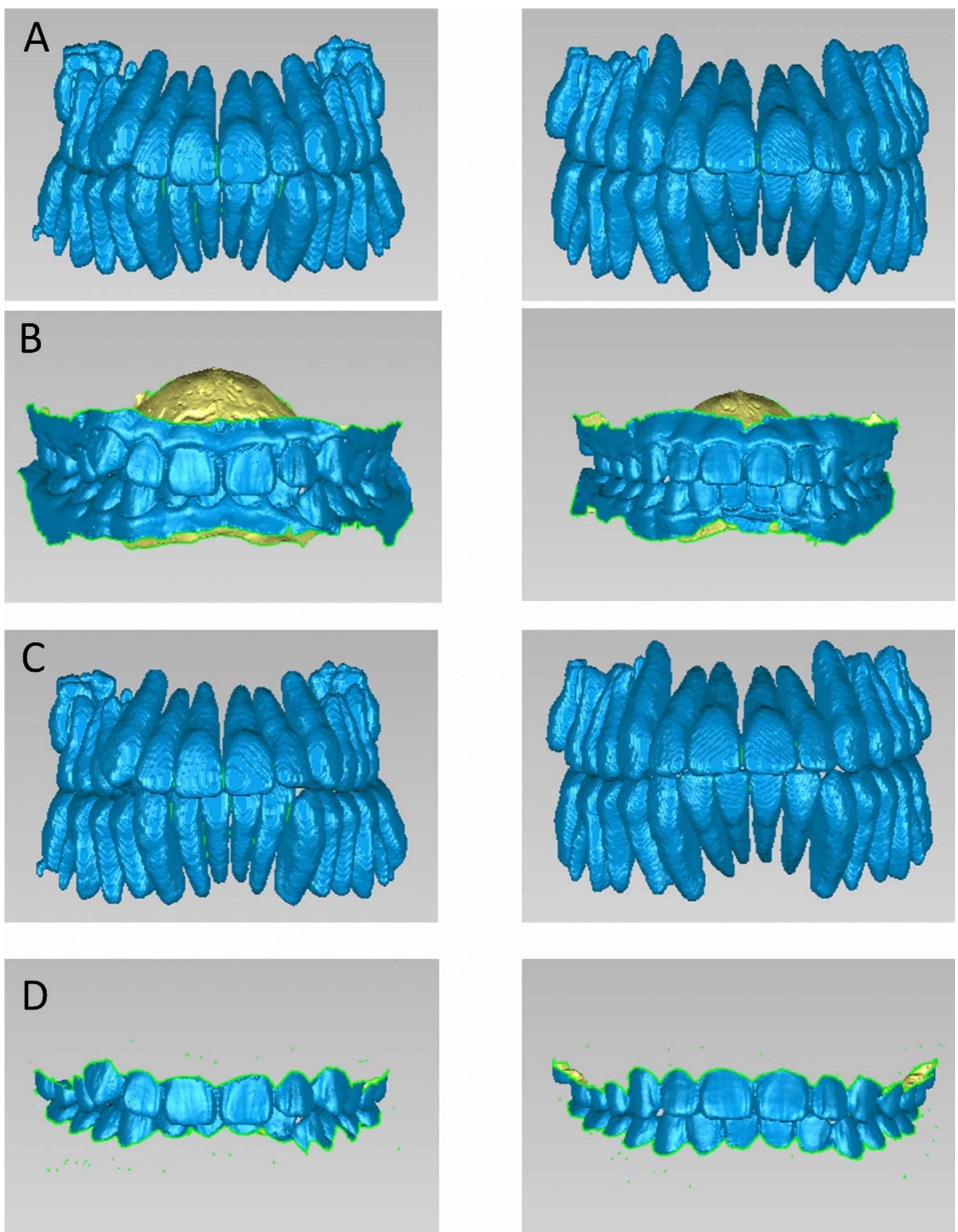

Fig. 1 The crown from the intraoral scan and roots extracted from Cone-Beam Computed Tomography (CBCT): **A** and **B**, original models; **C** and **D**, modified models

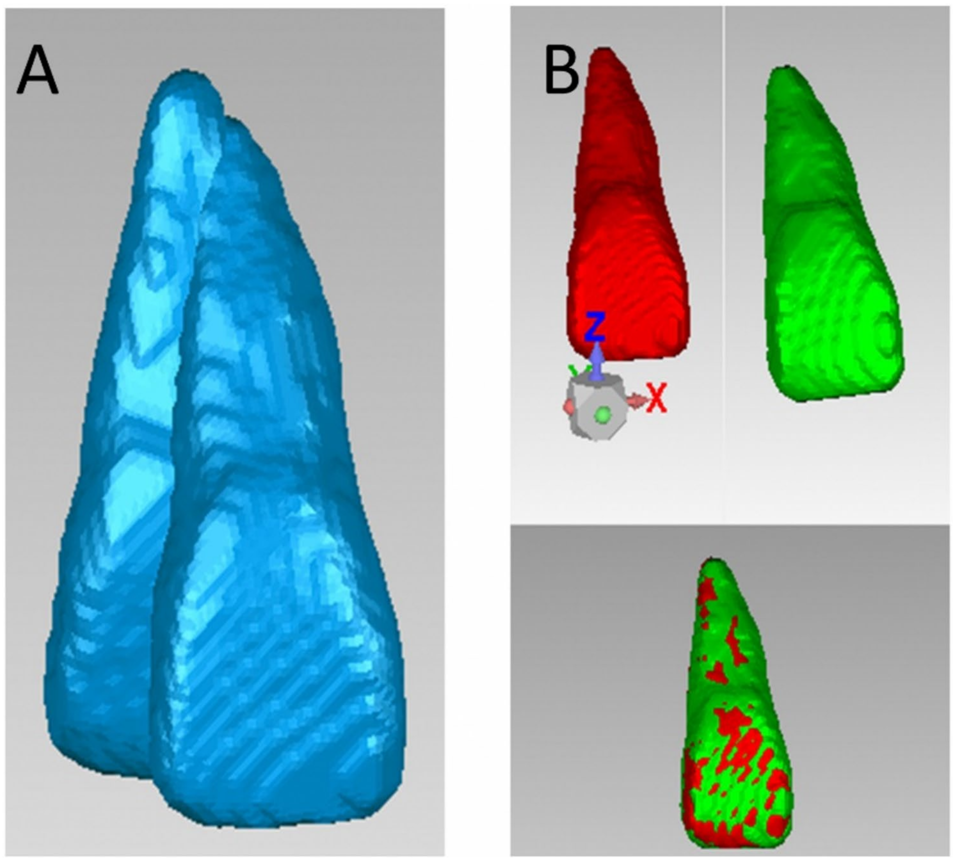

Fig. 2 The registration of teeth includes the following: **A**. The tooth models at pretreatment (T0) and posttreatment (T1); **B**. Aligned dental models

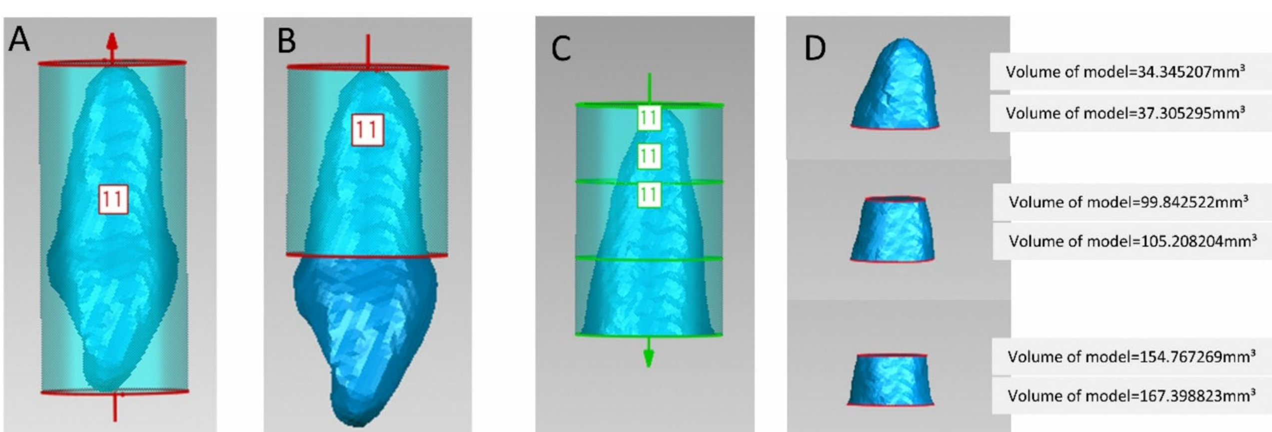

Fig. 3 Tooth and root segmentation and volumetric calculation in partition: **A**. Fitting a cylinder by aligning it with the shape of the tooth; **B**. Segmenting the root using a reference plane perpendicular to the long axis of the cylinder, passing through the highest point of the labial cemento-enamel junction; **C**. Partitioning the root into three equal parts based on the height of the cylinder; **D**. Calculating the volume of each part before and after orthodontic treatment

Intercept and partition of root as well as volume computation

A cylinder was fitted to the aligned tooth model to establish the long axis. A reference plane, perpendicular to this long axis and passing through the labial cemento-enamel junction (CEJ), was created to divide the tooth into its crown and root portions (Fig. 3). The root portion was subsequently segmented into three sections: the cervical third, middle third, and apical third. The volumes of these root segments were quantified using Geomagic software. The decrease in root volume at T1 compared to T0 was

Table 1 Wilcoxon signed-rank test comparison of root volume before and after orthodontics, median amount of ERR change and ERR percentage

Groups	Sample Size	Root volume, mm^3 Median (P25, P75)		Wilcoxon signed-rank test	ERR, mm3 Median (P25, P75)	ERR, % Median (P25, P75)
		T0	T1	*P* Value		
I	459	299.45 231.73, 407.06)	283.43 (217.55, 411.10)	0.000*	11.30 (0.00, 29.02)	4.51 (0.14, 10.04)
II	456	290.20 (216.10, 418.70)	264.77 (194.67, 399.19)	0.000*	13.07 (3.33, 34.70)	5.20 (1.47, 12.48)

*P< 0.05 indicates statistical significance

Abbreviation. Group I (aged 10–15 year-old) and Group II (aged > 15 year-old); ERR: the decrease in root volume at posttreatment compared to pretreatment; T0: pretreatment, T1: posttreatment

defined as ERR. The percentage of ERR was calculated using the following formula:

$$\mathrm{ERR}\ (\%) = (\mathrm{Root\ volume\ loss} \ / \ \mathrm{Original\ root\ volume}) * 100\%$$

All measurements were performed by a single observer. To assess intra-observer reliability, the same procedure was repeated on 10% of the samples after a 4-week interval.

Statistics

Error assessment was performed using Dahlberg's index, within-observer repeatability, and intraclass correlation coefficients. All statistical analyses were conducted using IBM SPSS Statistics (version 21.0; IBM, Armonk, NY, USA).

The normality of the variables was assessed using the Kolmogorov-Smirnov test. Most variables did not follow a normal distribution. For variables that were not normally distributed, the non-parametric Wilcoxon signed-rank test was applied to compare root volumes at T0 and T1.

For variables following a normal distribution, independent samples were compared using the parametric Student's t-test to assess differences in ERR between groups, specifically in relation to tooth extraction during orthodontic treatment. For non-normally distributed variables, the non-parametric Mann–Whitney U test and Kruskal-Wallis test were used to examine differences in ERR distribution based on age, tooth position, root region, and extraction status. Statistical significance was defined as $P<0.05$.

Results

Changes in root volume before and after orthodontic treatment

A total of 36 patients and 915 teeth were assessed, with a random retest conducted on 10% of the samples. The intraclass correlation coefficient for the measurements was 0.99, indicating high reliability. Dahlberg's index was 1.2 mm^3, indicating a relatively small error compared to the overall root volume.

Table 2 Comparison of percentage of external root resorption (ERR) between anterior teeth and posterior teeth

Groups	Sample Size		ERR, % Median (P25, P75)		Mann–Whitney U tes
	Anterior teeth	Posterior teeth	Anterior teeth	Posterior teeth	*P* Value
I	213	246	6.71 (3.03, 12.08)	1.97 (-2.24, 7.92)	0.000*
II	212	244	6.75 (2.99, 15.79)	3.59 (0.26, 10.03)	0.000*

*P< 0.05 indicates statistical significance

Abbreviation. Group I (aged 10–15 year-old) and Group II (aged > 15 year-old); ERR: the decrease in root volume at posttreatment compared to pretreatment; T0: pretreatment, T1: posttreatment

As shown in Table 1, a statistically significant reduction in root volume was observed between T0 and T1 in both groups ($P<0.001$). The decrease in root volume after orthodontic treatment reflects significant root resorption in both Group I and Group II.

Variations in root resorption among different tooth type

The comparison of ERR between anterior and posterior teeth revealed significant differences ($P<0.001$), with anterior teeth showing greater ERR than posterior teeth in both groups (Table 2).

When comparing ERR between maxillary and mandibular teeth, no significant differences were observed for either anterior or posterior teeth, except for the posterior teeth in Group I. In Group I, mandibular posterior teeth exhibited significantly higher ERR than maxillary posterior teeth ($P<0.05$) (Table 3).

Variations in external root resorption among different root locations

The percentages of ERR at 3 different root locations are presented in Table 4. Statistically significant differences were observed across the cervical, middle, and apical thirds of the root ($P<0.001$). The apical third showed

Table 3 Mann–Whitney U test comparison of percentage of external root resorption (ERR) between the maxilla and the mandible classified by age group and teeth type (anterior and posterior teeth)

	Sample Size		ERR, % Median (P25, P75)		Mann–Whitney U test
	Maxillary	**Mandible**	**Maxillary**	**Mandible**	***P* Value**
Group I					
Anterior teeth	106	107	6.75 (3.10, 11.50)	6.77(2.70, 14.18)	0.686
Posterior teeth	120	126	0.90 (-2.71, 7.41)	2.85 (-0.79,8.56)	0.040*
Group II					
Anterior teeth	106	106	7.14 (3.23, 14.32)	6.24 (2.43,17.77)	0.851
Posterior teeth	116	128	3.17 (0.05, 10.34)	3.99 (0.35, 9.98)	0.625

*P< 0.05 indicates statistical significance

Abbreviation. Group I (aged 10–15 year-old) and Group II (aged > 15 year-old); ERR: the decrease in root volume at posttreatment compared to pretreatment

Table 4 Kruskal-Wallis test comparison of percentage of external root resorption (ERR) among 3 different locations of the root (cervical third, middle third and apical third)

Groups	Sample Size			ERR, % Median (P25, P75)			Kruskal-Wallis test
	Cervical third	**Middle third**	**Apical third**	**Cervical third**	**Middle third**	**Apical third**	***P* Value**
I	459	459	455	2.31 (-0.27, 7.29)	5.48 (0.84, 12.19)	9.98 (-3.67, 23.26)	0.000*
II	456	456	456	1.52 (-0.56, 6.82)	5.83 (1.20, 12.07)	16.66 (5.72,32.72)	0.000*

*P< 0.05 indicates statistical significance

Abbreviation. Group I (aged 10–15 year-old) and Group II (aged > 15 year-old); ERR: the decrease in root volume at posttreatment compared to pretreatment

Table 5 Comparison of percentage of external root resorption (ERR) in maxillary anterior teeth between extraction and non-extraction

Groups	Sample Size		ERR, % (Mean ± SD) / Median (P25, P75)		*P* Value [ab]
	Extraction treatment	**Non-extraction treatment**	**Extraction treatment**	**Non-extraction treatment**	
I	72	34	7.96 ± 6.77	5.83 ± 4.75	0.101[a]
II	54	52	8.97(4.42,16.70)	5,31(2.66,13.62)	0.018*[b]

*P< 0.05 indicates statistical significance

[a] indicates Student's t-test, [b] indicates Mann–Whitney U test

Abbreviation. Group I (aged 10–15 year-old) and Group II (aged > 15 year-old); ERR: the decrease in root volume at posttreatment compared to pretreatment

Table 6 Mann–Whitney U test comparison of percentage of external root resorption (ERR) between different age groups, classified by 4 types of region of the root

Region of the root	Sample Size		ERR, % Median (P25, P75)		Mann–Whitney U test
	Group I	**Group II**	**Group I**	**Group II**	***P* Value**
Total volume	459	456	4.53 (0.25, 10.04)	5.20 (1.47, 12.48)	0.001*
Apical third	459	456	9.99 (-2.98, 23.30)	16.66 (5.72, 32.72)	0.000*
Middle third	459	456	5.54 (1.07, 12.18)	5.82 (1.19,12.07)	0.221
Cervical third	455	456	2.38 (-0.03,7.29)	1.52 (-0.56, 6.82)	0.028*

*P< 0.05 indicates statistical significance

Abbreviation. Group I (aged 10–15 year-old) and Group II (aged > 15 year-old); ERR: the decrease in root volume at posttreatment compared to pretreatment

the highest level of ERR, followed by the middle third, while the cervical third exhibited the lowest percentage of resorption.

Variations in external root resorption between between extraction and non-extraction in maxillary anterior teeth

The comparison of ERR between extraction and non-extraction orthodontic treatments in maxillary anterior teeth is shown in Table 5. In Group I, no statistically significant difference in ERR was found between extraction and non-extraction treatments ($P > 0.05$) (Table 5). However, in Group II, the ERR in the extraction group was significantly higher than in the non-extraction group ($P < 0.05$) (Table 5).

Comparison of external root resorption between different age groups

Table 6 presents the percentages of ERR for total tooth roots and different root regions in both groups. Overall, Group I exhibited significantly less root resorption compared to Group II ($P < 0.05$), with particularly lower levels of ERR in the apical third of the roots ($P < 0.05$).

Conversely, Group I demonstrated significantly higher ERR in the cervical third compared to Group II ($P < 0.05$). No statistically significant difference was found between the two groups for ERR in the middle third of the root.

Discuss

ERR, defined as the permanent loss of hard tissue from the tooth root, is a common and often concerning consequence of orthodontic treatment [25]. Although the severity of ERR can differ between patients, it is a common concern in orthodontics, which continues to be an area of active research [28]. As the understanding of ERR deepens, recent advances in AI and automatic registration algorithms have enabled more detailed three-dimensional quantification of partitioned root volumes, providing valuable insights into this critical issue.

In previous studies, the process of 3D model reconstruction from CBCT for ERR analysis relied heavily on manual threshold segmentation. However, this method is prone to subjective variation between researchers and is often time-consuming [21]. AI technology offers a promising solution to these limitations. For instance, Trelenberg-Stoll et al. demonstrated that automated tooth segmentation, powered by AI, achieved accuracy comparable to the slice-by-slice manual segmentation method, which is regarded as the gold standard. Moreover, the AI method was approximately 81% faster than manual segmentation, significantly improving efficiency in clinical and research settings [29]. Similarly, Zhao et al. showed that their deep learning-based 3D tooth segmentation algorithm outperforms existing state-of-the-art methods in both accuracy and processing speed [22].

Beyond its application in root segmentation, AI is increasingly being integrated into various aspects of orthodontics, from diagnosis to treatment planning and outcomes measurement [30, 31]. This progress suggests that AI will play an increasingly central role in enhancing the precision and efficiency of orthodontic care, particularly in quantifying and managing ERR.

As ERR usually affects only a small part of the tooth, the root is often divided to measure it. However, the choice of cut plane or cut point is crucial to ensure accurate measurements, particularly when comparing models before and after treatment. In this study, we used a cylinder fitted to the surface of well-aligned models at T0 and T1 to define the long axis for segmentation (Fig. 3). This approach contrasts with previous studies [20], where manual point placement was required. By automatically generating the long axis in conjunction with the CEJ, our method facilitates the precise separation of the root from the crown. This novel approach not only simplified the measurement process but also improved the accuracy of the ERR quantification.

The resolution and size of CBCT scans are crucial for accurate ERR assessment. Higher accuracy is achieved with high-resolution images (e.g., 0.125 mm voxel size) [32]. In this study, CBCT scans with a 0.4 mm voxel size were used, providing sufficient resolution for relatively accurate results.

The findings of this study are consistent with those of previous research, which suggests a clear pattern of ERR related to tooth position and root region: orthodontic treatment inevitably leads to a reduction in root volume [12, 33, 34]. The degree of root volume reduction is typically greater in the anterior teeth compared to the posterior teeth, with the effect being especially pronounced in the anterior segment of the maxilla following tooth extraction [26]. Moreover, ERR is most notable in the apical third of the root [35]. In this study, both Group I and Group II showed varying degrees of root volume reduction (Table 1), with anterior teeth experiencing a more significant reduction than posterior teeth (Table 2). This effect was particularly pronounced in the maxillary anterior teeth following tooth extraction in Group II (Table 5). As shown in Table 4, the apical third of the roots exhibited the greatest degree of ERR.

In contrast to previous findings, no statistically significant difference was observed in the ERR of maxillary anterior teeth between the two groups. However, in the posterior teeth, Group I exhibited significantly higher ERR in the mandible (Table 3). Three potential explanations for this lack of difference can be proposed. First, the discrepancy may be due to an insufficient sample size. Second, the variation could be related to the degree of root development [7, 36]. Third, the CBCT scans were performed with a voxel size 0.4 mm, which may have led to an underestimation of the true extent of ERR.

In the study by Li et al. on the relationship between tooth root development and ERR, it was demonstrated that teeth with incomplete root development experience less ERR compared to those with fully developed roots [7, 36]. This finding was also observed in the current study, as shown in Table 6, which compares ERR between two age groups. The results indicated that Group II had a higher ERR rate than Group I. Furthermore, the study examined the ERR percentages at different root positions in both groups. The findings revealed that in the apical third of the root, the ERR percentage was higher in Group II than in Group I.

Patients in Group I, aged 10 to 15 years, likely have incomplete root development in some teeth, with ongoing growth in the apical region. This continued development may help mitigate the reduction in root volume caused by orthodontic treatment. In contrast, patients in Group II have nearly fully developed teeth in the apical region, and the apical area no longer undergoes growth during treatment, leading to more significant

ERR compared to Group I. Thus, it appears that younger orthodontic patients may have an advantage over older patients in terms of reducing ERR.

While our study has demonstrated significant advancements in the quantification of ERR using AI-driven techniques, it is imperative to consider the clinical implications of these findings. Our observation of greater root resorption in anterior teeth, particularly in the apical third, and the exacerbating effect of extraction strongly underscores the need for cautious treatment planning in these cases. Clinicians should exercise heightened vigilance when monitoring the roots of anterior teeth in patients undergoing extraction therapy, employing frequent radiographic evaluations to detect early signs of significant ERR. Additionally, our finding of less ERR in younger patients with ongoing root development offers a valuable clinical insight, suggesting that treatment planning for younger patients requiring substantial tooth movement or extraction might yield more favorable outcomes with reduced risks of severe root resorption. These results emphasize the importance of individualized treatment planning, tailored to the patient's specific age, tooth type, and treatment requirements.

Limitations

This study presents several limitations that warrant careful consideration. Firstly, due to the retrospective design and the limited number of cases that met our inclusion criteria, precluded the performance of a robust power analysis. This methodological constraint may limit the generalizability of our findings. Secondly, the 0.4 mm voxel size employed for CBCT imaging may not be adequate to capture subtle morphological alterations in root structure, potentially affecting the precision of ERR quantification. Thirdly, the clinical applicability of our methodology requires further validation to accurately assess ERR in a heterogeneous patient cohort. We acknowledge that our cylinder fitting approach has inherent limitations pertaining to tooth morphology. While the approach typically yielded reliable results in anterior teeth, the fitted cylinders in molars often demonstrated deviations from the true anatomical long axis. Furthermore, the scope of this study was limited to analyzing vertical changes in root morphology; future research should investigate volumetric changes in the labiolingual or buccolingual dimensions to provide a more comprehensive understanding of ERR.

Conclusion

1. This study developed a new method for assessing external root resorption, using automated image segmentation to improve efficiency and combining intraoral scans and reconstructed CBCT images into a composite model for more accurate volumetric measurement and comprehensive three-dimensional analysis.
2. The occurrence of external root resorption after orthodontic treatment may differ depending on tooth position, root region, and whether extraction treatment was performed.
3. Greater resorption is observed in the anterior teeth compared to the posterior teeth, with the most significant reduction occurring in the anterior maxillary segment following extraction treatment. Additionally, the apical third of the root shows the most pronounced resorption across all tooth regions.
4. Overall, external root resorption tends to be more pronounced in older patients, particularly in the apical third of the root.

Abbreviations

ERR	External root resorption
CBCT	Cone Beam Computed Tomography
CEJ	Cemento-enamel junction
2D	Two-dimensional
3D	There-dimensional
AI	Artificial intelligence
Group I	(aged 10–15 year-old)
Group II	(aged > 15 year-old)

Acknowledgements
Not applicable.

Author contributions
CSY conceived and designed the study. JH acquired, analyzed and interpreted the data, and was a major contributor to the writing of the manuscript. MJW, XT and LLZ critically revised the manuscript regarding its important intellectual content. All authors read and approved the final manuscript.

Funding
Not applicable.

Data availability
The datasets generated and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and was approved by the Institutional Review Board (IRB) of Chongqing Stomatological Hospital, Chongqing Medical University (Approval No. 2024-073). The clinical trial registration number is: Not applicable. For this research, informed consent was obtained from the parents or legal guardians of all children aged under 16 years. In addition, informed consent to participate form was signed by each participant in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 29 November 2024 / Accepted: 20 February 2025
Published online: 07 March 2025

References

1. Kuijpers-Jagtman AM, Persoon S, van Westing K, et al. Development of a clinical practice guideline for orthodontically induced external apical root resorption. Eur J Orthod. 2020;42:115–24.
2. Patel S, Saberi N, Pimental T, Teng PH. Present status and future directions: root resorption. Int Endod J. 2022;55(Suppl 4):892–921.
3. Kalra S, Gupta P, Tripathi T, Rai P. External apical root resorption in orthodontic patients: molecular and genetic basis. J Fam Med Prim Care. 2020;9(8):3872–82.
4. Liu W, Shao J, Li S, et al. Volumetric cone-beam computed tomography evaluation and risk factor analysis of external apical root resorption with clear aligner therapy. Angle Orthod. 2021;91:597–603.
5. Baysal A, Karadede I, Hekimoglu S, et al. Evaluation of root resorption following rapid maxillary expansion using cone-beam computed tomography. Angle Orthod. 2012;82:488–94.
6. Bayir F, Bolat Gumus E. External apical root resorption after orthodontic treatment: incidence, severity and risk factors. J Dent Res Dent Clin Dent Prospects. 2021;15:100–5.
7. de Almeida-Pedrin RR, de Almeida Cardoso M, Valarelli DP, et al. Comparative study of root resorption of maxillary incisors in patients treated with lingual and buccal orthodontics. Angle Orthod. 2017;87:795–800.
8. Coutsiers Morell GF, Berlin-Broner Y, Flores-Mir C, Heo G. Tooth and root size as determined from 0.25- and 0.30-mm voxel size cone-beam CT imaging when contrasted to micro-CT scans (0.06 mm): an ex vivo study. J Orthod. 2022;49:174–8.
9. Puttaravuttiporn P, Wongsuwanlert M, Charoemratrote C, Leethanakul C. Volumetric evaluation of root resorption on the upper incisors using cone beam computed tomography after 1 year of orthodontic treatment in adult patients with marginal bone loss. Angle Orthod. 2018;88:710–8.
10. Pairatchawan N, Viteporn S, Thongudomporn U. Mandibular incisor root volume changes between anterior bite planes fabricated from acrylic resin and thermoplastic materials: a prospective randomized clinical trial. Angle Orthod. 2022;92:755–63.
11. Li C, Teixeira H, Tanna N, et al. The reliability of Two- and Three-Dimensional cephalometric measurements: A CBCT study. Diagnostics (Basel). 2021;11(12):2292.
12. Jung Y-H, Cho B-H. External root resorption after orthodontic treatment: A study of contributing factors. Imaging Sci Dent. 2011;41(1):17–21.
13. Lee J-H, Byun S-H, Yi S-M, et al. Efficacy of constructing digital hybrid Skull-Dentition images using an intraoral scanner and Cone-Beam computed tomography. Scanning. 2022;2022:1–9.
14. Dudic A, Giannopoulou C, Meda P, Montet X, Kiliaridis S. Orthodontically induced cervical root resorption in humans is associated with the amount of tooth movement. Eur J Orthod. 2017;39:534–40.
15. Lund H, Gröndahl K, Hansen K, Gröndahl H-G. Apical root resorption during orthodontic treatment. Angle Orthod. 2012;82:480–7.
16. Deng Y, Sun Y, Xu T. Evaluation of root resorption after comprehensive orthodontic treatment using cone beam computed tomography (CBCT): a meta-analysis. BMC Oral Health. 2018;18(1):116.
17. Brusveen EM, Brudvik P, Bøe OE, Mavragani M. Apical root resorption of incisors after orthodontic treatment of impacted maxillary canines: a radiographic study. Am J Orthod Dentofac Orthop. 2012;141:427–35.
18. Leonardi R, Ronsivalle V, Isola G, et al. External root resorption and rapid maxillary expansion in the short-term: a CBCT comparative study between tooth-borne and bone-borne appliances, using 3D imaging digital technology. BMC Oral Health. 2023;23:558.
19. Pereira ABN, Almeida R, Artese F, Dardengo C, Quintão C, Carvalho F. External root resorption evaluated by CBCT 3D models superimposition. Dent Press J Orthod. 2022;27:e2219315.
20. Leonardi R, Ronsivalle V, Barbato E, Lagravère M, Flores-Mir C, Lo Giudice A. External root resorption (ERR) and rapid maxillary expansion (RME) at post-retention stage: a comparison between tooth-borne and bone-borne RME. Prog Orthod. 2022;23:45.
21. Lee S-C, Hwang H-S, Lee KC. Accuracy of deep learning-based integrated tooth models by merging intraoral scans and CBCT scans for 3D evaluation of root position during orthodontic treatment. Prog Orthod. 2022;23(1):15.
22. Zhao Y, Zhang L, Yang C, et al. 3D dental model segmentation with graph attentional Convolution network. Pattern Recognit Lett. 2021;152:79–85.
23. Lim S-W, Moon R-J, Kim M-S, et al. Construction reproducibility of a composite tooth model composed of an intraoral-scanned crown and a cone-beam computed tomography-scanned root. Korean J Orthod. 2020;50:229–37.
24. Akl HE, El-Beialy AR, El-Ghafour MA, Abouelezz AM, El Sharaby FA. Root resorption associated with maxillary buccal segment intrusion using variable force magnitudes. Angle Orthod. 2021;91:733–42.
25. Zhang X, Zhou H, Liao X, Liu Y. The influence of bracket torque on external apical root resorption in bimaxillary protrusion patients: a retrospective study. BMC Oral Health. 2022;22:7.
26. Li X, Xu J, Yin Y, et al. Association between root resorption and tooth development: A quantitative clinical study. Am J Orthod Dentofac Orthop. 2020;157:602–10.
27. Hu X, Zhao Y, Yang C. Evaluation of root position during orthodontic treatment via multiple intraoral scans with automated registration technology. Am J Orthod Dentofac Orthop. 2023;164:285–92.
28. Samandara A, Papageorgiou SN, Ioannidou-Marathiotou I, Kavvadia-Tsatala S, Papadopoulos MA. Evaluation of orthodontically induced external root resorption following orthodontic treatment using cone beam computed tomography (CBCT): a systematic review and meta-analysis. Eur J Orthod. 2019;41:67–79.
29. Trelenberg-Stoll V, Drescher D, Wolf M, Becker K. Automated tooth segmentation as an innovative tool to assess 3D-tooth movement and root resorption in rodents. Head Face Med. 2021;17:3.
30. Zhu J, Yang Y, Wong HM. Development and accuracy of artificial intelligence-generated prediction of facial changes in orthodontic treatment: a scoping review. J Zhejiang Univ Sci B. 2023;24:974–84.
31. Al-Ubaydi AS, Al-Groosh D. The validity and reliability of automatic tooth segmentation generated using artificial intelligence. Sci. World J. 2023;2023:5933003.
32. Dabbaghi A, Sharifi S, Esmaeili M. Accuracy of High- and Low-Resolution Cone-Beam computed tomographic scans in the detection of impacted Tooth-Induced external root resorption: an Ex-Vivo study. Front Dent. 2019;16(6):429–35.
33. Apajalahti S, Peltola JS. Apical root resorption after orthodontic treatment a retrospective study. Eur J Orthod. 2007;29:408–12.
34. Jiang Rp, McDonald JP, Fu M. Root resorption before and after orthodontic treatment: A clinical study of contributory factors. Eur J Orthod. 2010;32:693–7.
35. Kalina E, Grzebyta A, Zadurska M. Bone remodeling during orthodontic movement of lower incisors—narrative review. Int J Environ Res Public Health. 2022;19:15002.
36. Dudic A, Giannopoulou C, Martinez MMX. S K. Diagnostic accuracy of digitized periapical radiographs validated against micro-computed tomography scanning in evaluating orthodontically induced apical root resorption. Eur J Oral Sci. 2008;467– 72.

Publisher's note