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Quantitative analysis and clinical determinants of orthodontically induced root resorption using automated tooth segmentation from CBCT imaging

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Abstract

Background Orthodontically induced root resorption (OIRR) is difficult to assess accurately using traditional 2D imaging due to distortion and low sensitivity. While CBCT offers more precise 3D evaluation, manual segmentation remains labor-intensive and prone to variability. Recent advances in deep learning enable automatic, accurate tooth segmentation from CBCT images. This study applies deep learning and CBCT technology to quantify OIRR and analyze its risk factors, aiming to improve assessment accuracy, efficiency, and clinical decision-making.

Method This study retrospectively analyzed CBCT scans of 108 orthodontic patients to assess OIRR using deep learning-based tooth segmentation and volumetric analysis. Statistical analysis was performed using linear regression to evaluate the influence of patient-related factors. A significance level of $p < 0.05$ was considered statistically significant.

Results Root volume significantly decreased after orthodontic treatment ($p < 0.001$). Age, gender, open (deep) bite, severe crowding, and other factors significantly influenced root resorption rates in different tooth positions. Multivariable regression analysis showed these factors can predict root resorption, explaining 3% to 15.4% of the variance.

Conclusion This study applied a deep learning model to accurately assess root volume changes using CBCT, revealing significant root volume reduction after orthodontic treatment. It found that underage patients experienced less root resorption, while factors like anterior open bite and deep overbite influenced resorption in specific teeth, though skeletal pattern, overjet, and underbite were not significant predictors.

Keywords Orthodontically induced root resorption, Cone-beam computed tomography, Risk factor, Linear regression

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Introduction

Tooth root resorption is a common sequel to injury or inflammation affecting the periodontal ligament or dental pulp. This physiological or pathological process leads to the progressive destruction and eventual loss of tooth root dentin and cementum [1, 2], potentially compromising the structural integrity and longevity of the affected teeth. The resorption process can originate either within the root structure or on its external surface, leading to the classification of tooth root resorption into two main types: internal resorption and external resorption [3]. Internal resorption occurs within the pulp chamber or root canal, often due to chronic pulp inflammation, trauma, or infection. In contrast, external resorption is more common and can be further categorized into several subtypes, including surface resorption, inflammatory resorption, and replacement resorption, depending on its etiology and progression.

One specific form of external resorption is orthodontically induced root resorption (OIRR), which is a sterile inflammatory process resulting from the mechanical forces applied to facilitate tooth movement during orthodontic treatment [4]. The prevalence of OIRR varies, with studies indicating that approximately 40%–60% of orthodontic patients experience mild to moderate levels of root resorption, while severe cases occur in 1%–5% of patients [5]. The extent of OIRR can be influenced by multiple factors, making its prediction and prevention a significant concern in orthodontics.

From a clinical perspective, early detection and risk prediction of OIRR are essential for minimizing potential adverse outcomes. The etiology of OIRR is multifactorial, involving a combination of patient-related and treatment-related factors. Patient-related factors include demographic variables such as age and gender [6], underlying malocclusion [7], and individual tooth anatomy, all of which may contribute to varying degrees of susceptibility to root resorption. However, despite extensive research, the correlation between these factors and root resorption remains inconclusive [8]. Differences in study methodologies, patient populations, and imaging techniques have contributed to conflicting findings, making it challenging to establish definitive predictive factors for OIRR. On the other hand, treatment-related factors such as force magnitude, duration, direction of tooth movement, and the type of orthodontic appliance used also play a significant role in determining the extent of root resorption [9, 10].

Historically, the quantification of OIRR has relied on two-dimensional (2D) radiological methods, including panoramic, periapical, and cephalometric radiographs [8, 11–13]. These imaging modalities have been widely used due to their accessibility and relatively low radiation exposure. However, their inherent limitations—such as superimposition of structures, geometric distortion, and difficulty in visualizing fine root details—often lead to inaccuracies in landmark identification and measurement inconsistencies. These limitations have prompted researchers and clinicians to seek more advanced imaging techniques for assessing root resorption.

With the advent of cone beam computed tomography (CBCT), high-resolution three-dimensional (3D) volumetric data of tooth roots can now be obtained with greater accuracy and sensitivity [14, 15]. CBCT imaging allows for more precise assessment of root morphology and volume changes before and after orthodontic treatment. However, traditional methods for extracting and analyzing these 3D root volumetric data have relied heavily on manual tooth segmentation, a time-consuming and labor-intensive process that requires expert intervention and is prone to inter- and intra-observer variability [16–19].

Encouraged by the remarkable advancements in deep learning and artificial intelligence in the field of medical imaging, recent studies have explored the application of automated deep learning-based models for tooth segmentation. These models have demonstrated high accuracy in segmenting teeth from CBCT images, thereby simplifying the workflow and reducing human effort in analyzing root volume changes. The integration of deep learning into dental radiology has significantly improved the efficiency, objectivity, and reproducibility of OIRR assessments, making large-scale studies more feasible [20–24].

The primary objective of this study was to quantify root volume loss as a measure of OIRR using a fully automated deep learning-based segmentation system [25] applied to CBCT data. The null hypothesis of this study was that there is no significant root volume loss after orthodontic treatment and that patient-related variables have no predictive value for OIRR. By focusing on a homogeneous sample of patients treated with fixed aligners by the same orthodontist, this study aimed to explore the incidence and severity of OIRR and to evaluate the influence of specific patient-related factors on root resorption.

Material and methods

Research design, participant selection and sample size

The study was retrospective in design and was reviewed and approved by the Ethics Committee of the Affiliated Hospital of Stomatology, School of Stomatology, Zhejiang University School of Medicine (2024–001[R]). All images were essential for model training and clinical validation, ensuring that patient-specific information was anonymized in compliance with ethical standards. This study was conducted in accordance with the principles of the Declaration of Helsinki. Informed consent was obtained from all participants for the use of data.

A minimum sample size of 108 patients was post-hoc calculated for a multivariable linear regression analysis, assuming a medium effect of 0.15, nine predictors (including the constant), 80 per cent power of the test and 5 per cent level of significance. A total of 108 patients were selected, who had underwent comprehensive orthodontic treatment using fixed orthodontic appliances with good quality pre- and post-treatment CBCT images at the Department of Orthodontics, The Affiliated Hospital of Stomatology, School of Stomatology, Zhejiang University School of Medicine. Exclusion criteria were craniofacial anomalies, history of severe craniomaxillofacial trauma and systemic disease or syndromes. Both pretreatment (T0) and posttreatment (T1) CBCT scans were obtained with a NewTom VGi scanner (QR Srl, Verona, Italy) with the following acquisition conditions: 110 kV; 2 mA; voxel size, 0.3 mm; scanning time, 3.6 s; and volume, 15 cm × 15 cm. Root resorption was assessed in the CBCT scans for incisors, canines, premolars, and first molars at T0-T1 time. All the scans were saved in Digital Imaging and Communication in Medicine (DICOM) format.

Patient-related factors including gender, age, skeletal pattern, presence of overbite, overjet, under bite, open bite and moderate to severe crowding were noted.

Root resorption assessment

The steps of the OIRR assessment protocol consisted of individual tooth segmentation, acquisition of root volume data and calculation of root loss. The segmentation of individual tooth in CBCT images at each time-point was conducted using a deep learning based system developed by Cui et al. [25–27], which achieve stable and accurate tooth segmentation based on a three stage neural network structure. In addition, the results obtained from the deep learning system were manually corrected by a professional orthodontic clinician to ensure their accuracy. The segmentation outcome was generation of a virtual 3D model of each tooth in Standard Tessellation Language (STL) file format (Fig. 1).

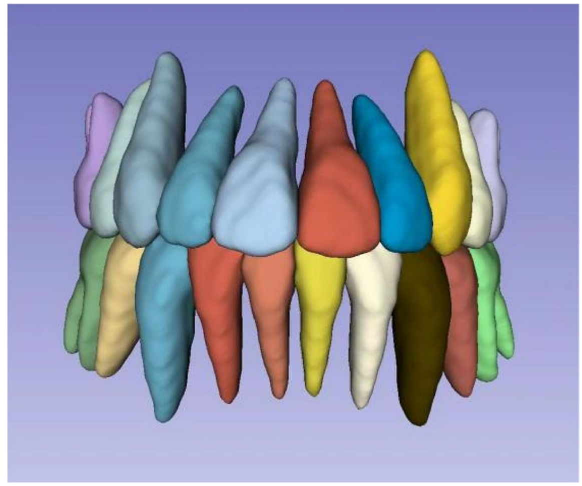

Fig. 1 Automated segmentation result

Measurement of root volume was carried out in Mimics Research 19.0 software (IBM, Armonk, NY). The 3D model of each tooth was imported and the cemento-enamel junction (CEJ) was located according to the morphology of tooth neck (Fig. 2). Percentage of root loss (%) =(pretreatment root volume—posttreatment root volume)/(pretreatment root volume) ×100%. The severity of OIRR was divided into the following three degrees according to the percentage of root loss: no root reorption, mild (< 10%), moderate (10%–20%) and severe (> 20%) root resorption [16]. Reassessment of pre- and post-treatment tooth volume was performed in 35 randomly selected patients by a single operator.

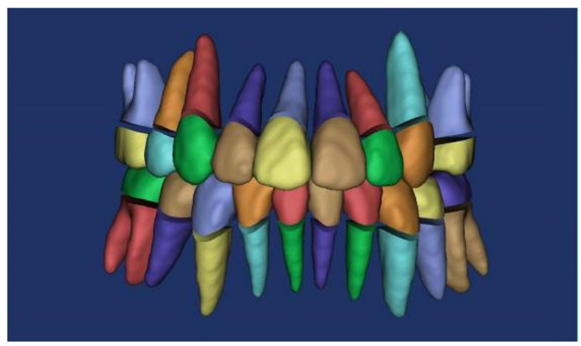

Fig. 2 Separation of tooth crown and root based on CEJ

Statistical analysis

Statistical analysis were performed using Microsoft Excel (version 2019; Microsoft, Redmond, Wash) and Scientific Platform Serving for Statistics Professional 2021. SPSSPRO. (Version 1.0.11). Continuous data were shown as mean and standard deviation, while categorical variables were shown as number of patients and percentages. The statistical differences in the root volume between the pre- and posttreatment were evaluated by paired t-test. Linear regression was performed for the determination of patient-related factors in OIRR. First, the effect of explanatory variables on OIRR was assessed using univariable linear regression analysis. To create a regression equation, a multi-variable regression model including significant predictors of OIRR at the 0.05 level was constructed. Intraclass correlation coefficients (ICCs) were used to assess the interoperator reliabilities. The ICC

Table 1 Demographic distribution and malocclusion characteristics of patients

Variables		n	%
Age	Adult	52	48.2
	Underage	56	51.8
Gender	Male	33	30.6
	Female	75	69.4
Skeletal pattern	Class I	77	71.3
	Class II	17	15.7
	Class III	14	13.0
Deep overbite	Exist	18	16.7
	Non-exist	90	83.3
Deep overjet	Exist	53	49.0
	Non-exist	55	51.0
Crossbite	Exist	10	9.3
	Non-exist	98	90.7
Openbite	Exist	8	7.4
	Non-exist	100	92.6
Maxillary crowding	Exist	63	58.3
	Non-exist	45	41.7
Mandibular crowding	Exist	67	62.0
	Non-exist	41	38.0

n number, *%* percentage

calculated for each tooth ranged between 0.856 and 0.974, indicating that the evaluation method was reliable.

Results

The study evaluated root volume loss in 2312 teeth from 108 patients. The demographic and malocclusions characteristics distribution of the patients were shown in Table 1 as absolute numbers and percentages for categorical variables (gender, skeletal pattern and presence of deep overbite, deep overjet, under bite, open bite, severe crowding). Table 2 showed the statistics of root volume pre- and post-treatment and Table 3 showed the frequency distribution of root resorption after orthodontic treatment. Compared to pre-treatment, a statistically significant root volume reduced ($p < 0.001$) was observed after orthodontic treatment (Table 2).

From the univariable linear regression analyses for the patient-related factors of OIRR in different tooth position (Tables 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13), age showed significant impacts on root resorption rate of all teeth involved in orthodontic treatment except maxillary molars. Gender had significant impacts on root resorption rate of maxillary central incisors, lateral incisors, canines and mandibular canines ($p < 0.05$). Existence of openbite showed significant impacts on root resorption rate of maxillary central incisors and lateral incisors ($p < 0.05$), while deep overbite showed a significant impact on root resorption rate of maxillary molar ($p = 0.045$). Besides, maxillary moderate to severe crowding showed significant impacts on root resorption rate of maxillary premolars and molars ($p < 0.05$), while mandibular moderate to severe crowding showed significant impacts on root resorption rate of maxillary premolars and mandibular premolars ($p < 0.05$). Other patient-related factors were not significantly associated with root resorption rate during orthodontic treatment.

The multivariable regression analyses, including factors confirmed the significance in predicting root resorption rate during orthodontic treatment was then performed in maxillary central incisor (F = 14.019 $P = 0.000^{***}$), lateral incisors (F = 8.963 $P = 0.000^{***}$), canines (F = 8.963 $P = 0.000^{***}$), premolars (F = 19.349 $P = 0.000^{***}$) molars

Table 2 Root volume statistics after orthodontic treatment

	n	Pre-treatment(T1)		Post-treatment(T2)		Volume loss		*P* value
		Mean	SD	Mean	SD	Mean	SD	
Maxillary								
Central incisor	215	208.42	45.76	189.25	45.21	0.092	0.081	0.001***
Lateral incisor	210	176.48	42.26	160.61	42.18	0.093	0.085	0.001***
Canine	204	287.95	61.02	276.68	64.56	0.039	0.097	0.001***
Premolar	311	215.95	45.04	206.53	47.78	0.040	0.108	0.001***
Molar	214	433.43	77.44	406.65	76.85	0.065	0.047	0.001***
Mandibular								
Central incisor	211	106.07	23.89	98.89	22.00	0.062	0.106	0.001***
Lateral incisor	211	135.34	26.48	126.18	28.23	0.065	0.115	0.001***
Canine	214	245.73	52.66	235.70	54.08	0.041	0.085	0.001***
Premolar	317	187.30	37.00	180.72	37.00	0.032	0.098	0.001***
Molar	209	405.30	79.12	385.93	76.22	0.045	0.081	0.001***

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Table 3 Frequency and distribution of root resorption classification results

	n	%
No resorption	410	17.73
Mild	1281	55.41
Moderate	476	20.59
Severe	145	6.27
Total	2312	100

n number, % percentage

Table 4 Univariable linear regression analyses for the patient-related factors and root resorption in maxillary central incisors

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.054	0.01	0.332	0.000***
Underage	Reference	-	-	-
Gender				
Female	0.037	0.012	0.214	0.002**
Male	Reference	-	-	-
Skeletal pattern				
Class I	−0.005	0.017	−0.029	0.756
Class II	0.013	0.021	0.06	0.523
Class III	Reference	-	-	-
Deep overbite				
Exist	0.013	0.015	0.061	0.372
Non-exist	Reference	-	-	-
Deep overjet				
Exist	0.006	0.011	0.039	0.569
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.008	0.019	−0.027	0.690
Non-exist	Reference	-	-	-
Openbite				
Exist	0.052	0.021	0.169	0.013*
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	−0.017	0.011	−0.107	0.119
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.022	0.011	0.131	0.056
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Table 5 Univariable linear regression analyses for the patient-related factors and root resorption in maxillary lateral incisors

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.05	0.012	0.269	0.000***
Underage	Reference	-	-	-
Gender				
Female	0.028	0.014	0.138	0.046*
Male	Reference	-	-	-
Skeletal pattern				
Class I	−0.001	0.028	−0.006	0.964
Class II	0.007	0.032	0.027	0.828
Class III	Reference	-	-	-
Deep overbite				
Exist	0.016	0.017	0.063	0.361
Non-exist	Reference	-	-	-
Deep overjet				
Exist	0.003	0.013	0.016	0.818
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.005	0.022	−0.014	0.835
Non-exist	Reference	-	-	-
Openbite				
Exist	0.083	0.024	0.239	0.000***
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	−0.008	0.014	−0.043	0.565
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.002	0.013	0.012	0.862
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

(F =5.4 P= 0.005**), mandibular canines (F =14.393 P= 0.000***) and premolars (F =19.902 P= 0.000***). In terms of collinearity testing of variables, the VIF scores was all less than 5, which indicated that the model did not have multicollinearity problems. The regression equations, based on only significant predictors at the 0.05 level was presented in Table 14. The percentage of variation in root resorption explained by these equations varied from 3 to 15.4.

Discussion

OIRR (Orthodontic-Induced Root Resorption) is a common iatrogenic side effect observed in a majority of orthodontic patients. Traditional methods for quantifying OIRR predominantly involve evaluating changes in root length or morphology scores based on 2D panoramic radiographs. Moreover, most clinical studies on root resorption have primarily focused on maxillary incisors, with limited research examining root resorption across all teeth during orthodontic treatment. A recent study by Alqahtani et al. [28] demonstrated the effectiveness of an automated 3D tooth segmentation model for assessing root resorption following combined orthodontic and orthognathic surgical treatments. To standardize

Table 6 Univariable linear regression analyses for the patient-related factors and root resorption in maxillary canines

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.076	0.013	0.389	0.000***
Underage	Reference	-	-	-
Gender				
Female	0.03	0.015	0.141	0.045*
Male	Reference	-	-	-
Skeletal pattern				
Class I	−0.022	0.021	−0.101	0.296
Class II	0.014	0.025	0.054	0.576
Class III	Reference	-	-	-
Deep overbite				
Exist	0.03	0.018	0.114	0.104
Non-exist	Reference	-	-	-
Deep overjet				
Exist	0.008	0.014	0.039	0.581
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.018	0.032	−0.052	0.578
Non-exist	Reference	-	-	-
Openbite				
Exist	−0.012	0.025	−0.033	0.641
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	−0.003	0.014	−0.013	0.854
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.036	0.02	0.127	0.071
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Table 7 Univariable linear regression analyses for the patient-related factors and root resorption in maxillary premolars

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.077	0.012	0.353	0.000***
Underage	Reference	-	-	-
Gender				
Female	0.014	0.014	0.059	0.316
Male	Reference	-	-	-
Skeletal pattern				
Class I	−0.017	0.019	−0.067	0.391
Class II	0.024	0.024	0.078	0.371
Class III	Reference	-	-	-
Deep overbite				
Exist	0.008	0.016	0.03	0.620
Non-exist	Reference	-	-	-
Deep overjet				
Exist	0.014	0.012	0.064	0.258
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.019	0.021	−0.051	0.372
Non-exist	Reference	-	-	-
Openbite				
Exist	0.037	0.023	0.094	0.112
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	−0.036	0.012	−0.167	0.003**
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	−0.03	0.012	−0.137	0.016*
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

the process of root volume measurement from CBCT images, our study utilized a deep learning-based model for automatic tooth segmentation. This model achieved an impressive average Dice score of 92.4% for tooth segmentation, outperforming two expert radiologists (91.9% and 92.1%). Furthermore, the model's robustness and generalizability were evaluated and validated on the largest dataset to date. Our study is the first to comprehensively investigate OIRR using 3D quantitative data and explore its association with patient-related factors in a large sample size. Additionally, all patient samples in this study were treated by a single orthodontist, ensuring consistency in clinical procedures such as bonding, wire bending techniques, ligation methods, and orthodontic force levels throughout the treatment process.

Compared to pre-treatment measurements, a statistically significant reduction in average root volume was observed across all tooth positions following treatment. However, in some younger patients with incomplete root development before treatment, an increase in root volume was observed after treatment. Our findings are consistent with those of Wan et al. [16], who noted an increase in root volume in maxillary central incisors of mixed dentition patients (aged 7–11 years). However, unlike their study [11], our findings revealed that the increase in root volume following orthodontic treatment was not limited to maxillary central incisors. In fact, it was observed in all tooth positions and may also occur in patients with early permanent dentition (aged 12–17 years). Nonetheless, unlike our study, Kaya et al. [11] observed a significant amount of root resorption occurred in all teeth from patients aged 12–15 years during orthodontic treatment. This difference may be related with the radiological methods since the evaluation of root resorption was performed on panoramic radiographs in the study of Kaya et al. [11]. Evidence showed

Table 8 Univariable linear regression analyses for the patient-related factors and root resorption in maxillary molar

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.015	0.009	0.114	0.098
Underage	Reference	-	-	-
Gender				
Female	0.016	0.01	0.111	0.107
Male	Reference	-	-	-
Skeletal pattern				
Class I	0.012	0.013	0.084	0.365
Class II	0.032	0.017	0.175	0.060
Class III	Reference	-	-	-
Deep overbite				
Exist	0.024	0.012	0.137	0.045*
Non-exist	Reference	-	-	-
Deep overjet				
Exist	0.007	0.009	0.053	0.441
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.012	0.015	−0.054	0.435
Non-exist	Reference	-	-	-
Openbite				
Exist	0.016	0.017	0.063	0.361
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	−0.028	0.009	−0.208	0.002**
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.001	0.009	−0.002	0.978
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Table 9 Univariable linear regression analyses for the patient-related factors and root resorption in mandibular central incisors

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.045	0.016	0.191	0.005**
Underage	Reference	-	-	-
Gender				
Female	0.009	0.016	0.038	0.579
Male	Reference	-	-	-
Skeletal pattern				
Class I	−0.038	0.022	−0.165	0.077
Class II	−0.012	0.027	−0.041	0.656
Class III	Reference	-	-	-
Deep overbite				
Exist	0.013	0.022	0.044	0.563
Non-exist	Reference	-	-	-
Deep overjet				
Exist	−0.022	0.015	−0.106	0.124
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.029	0.036	−0.082	0.420
Non-exist	Reference	-	-	-
Openbite				
Exist	0.014	0.031	0.033	0.653
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	−0.023	0.016	−0.109	0.145
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.017	0.015	0.08	0.246
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

that development stage of tooth apical portion determined by CBCT might vary from panoramic radiographs because of the 2D image projection and superposition of adjacent maxillofacial structures appearing in panoramic radiographs [29].

We also calculated the classification results of root resorption to different degrees, indicating that mild absorption accounts for the highest proportion (55.41%), while the probability of severe absorption is the lowest (6.27%). This were basically consistent with the commonly accepted risk of root resorption [8], with a slightly higher proportion of severe resorption than generally believed (1–5%). Reasons for the increase might be differences in the evaluation criteria or variations in the patient samples. Additionally, traditional management of root resorption lesions based on 2D panoramic radiographs had inferior diagnostic accuracy compared to CBCT, which might also resulted in an underestimate of OIRR.

Regression analysis is a widely used tool in medical research to quantify the relationship between interdependent variables [30]. It can be classified as univariate or multivariate regression, as well as linear or nonlinear regression, depending on the number of independent variables and the nature of their relationship. Recently, Liu et al. [19] constructed a linear regression model to predict OIRR in incisors. This model included treatment-related factors such as post-treatment sagittal root position, extraction, tooth type, and intrusion and extrusion distances, achieving a predictive power of 0.51. However, since the assessment of root resorption risk is typically conducted prior to treatment, patient-related factors before treatment have gained attention from orthodontists. These factors can help predict the risk of OIRR from the outset of orthodontic treatment. This study mainly

Table 10 Univariable linear regression analyses for the patient-related factors and root resorption in mandibular lateral incisors

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.054	0.015	0.238	0.001**
Underage	Reference	-	-	-
Gender				
Female	0.027	0.018	0.107	0.129
Male	Reference	-	-	-
Skeletal pattern				
Class I	−0.041	0.034	−0.161	0.228
Class II	−0.001	0.039	−0.004	0.973
Class III	Reference	-	-	-
Deep overbite				
Exist	0.035	0.021	0.111	0.108
Non-exist	Reference	-	-	-
Deep overjet				
Exist	−0.013	0.017	−0.058	0.440
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.047	0.038	−0.121	0.218
Non-exist	Reference	-	-	-
Openbite				
Exist	0.015	0.03	0.034	0.633
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	−0.012	0.017	−0.051	0.494
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.013	0.016	0.056	0.417
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Table 11 Univariable linear regression analyses for the patient-related factors and root resorption in mandibular canines

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.054	0.011	0.318	0.000**
Underage	Reference	-	-	-
Gender				
Female	0.03	0.013	0.159	0.020*
Male	Reference	-	-	-
Skeletal pattern				
Class I	−0.042	0.017	−0.221	0.055
Class II	0.008	0.021	0.034	0.710
Class III	Reference	-	-	-
Deep overbite				
Exist	0.008	0.017	0.036	0.620
Non-exist	Reference	-	-	-
Deep overjet				
Exist	−0.011	0.013	−0.065	0.376
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.038	0.028	−0.13	0.176
Non-exist	Reference	-	-	-
Openbite				
Exist	−0.006	0.022	−0.019	0.787
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	0.014	0.012	0.083	0.240
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.012	0.021	0.039	0.568
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

involved univariate and multivariate linear regression models for determining whether the various patient-related factors can predict the risk of OIRR, in which the dependent variable was continuous and the independent variables were categorical.

Results of univariate regression demonstrated that age played an important role in predicting the severity of root resorption during orthodontic treatment. This finding was compatible with the findings presented by Li et al. [31], Levander et al. [32], Sehr et al. [33] and Linkous et al. [7] as the older patients (> 18 years) have a greater tendency toward severe root resorption. The explanation of these evidence mainly concerning with the association between root resorption and tooth development. Evidence shows that patients with immature teeth are at a much lower risk of apical root resorption [34]. Meanwhile, the root resorption risk of maxillary first molars was the only dependent variable unrelated to age in this study, which was generally due to their complete maturity at the beginning of orthodontic treatment. The results of this study also revealed that gender had significant linear effect on root resorption rate of maxillary central incisors, lateral incisors, canines and mandibular canines. Higher root resorption rate was observed in females compared with males in these teeth, which was compatible with the findings presented by most studies [10, 35, 36].

In this study, a linear negative correlation was observed between moderate to severe crowding with root resorption rate in premolars and molars. Although it is generally believed that that arch length deficiency is also not a risk factor, our findings were similar with the findings of Kaya et al. [11]. They suggested that the nonextraction treatment protocol which typically involved maxillary expansion as well as maxillary molar distalization, could attributed to OIRR [11]. Besides, anterior open bite

Table 12 Univariable linear regression analyses for the patient-related factors and root resorption in mandibular premolars

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.065	0.01	0.328	0.000***
Underage	Reference	-	-	-
Gender				
Female	0.018	0.013	0.083	0.155
Male	Reference	-	-	-
Skeletal pattern				
Class I	−0.037	0.025	−0.167	0.144
Class II	−0.038	0.028	−0.132	0.186
Class III	Reference	-	-	-
Deep overbite				
Exist	0.019	0.014	0.078	0.168
Non-exist	Reference	-	-	-
Deep overjet				
Exist	0.009	0.011	0.047	0.407
Non-exist	Reference	-	-	-
Crossbite				
Exist	−0.024	0.018	−0.075	0.182
Non-exist	Reference	-	-	-
Openbite				
Exist	0.043	0.019	0.125	0.260
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	0	0.012	0.001	0.993
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.027	0.011	0.135	0.016*
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Table 13 Univariable linear regression analyses for the patient-related factors and root resorption in mandibular molars

variable	B	Standard error	Beta	*P* value
Age				
Adult	0.033	0.011	0.205	0.003**
Underage	Reference	-	-	-
Gender				
Female	0.011	0.013	0.06	0.422
Male	Reference	-	-	-
Skeletal pattern				
Class I	0.012	0.025	0.064	0.649
Class II	0.013	0.03	0.058	0.657
Class III	Reference	-	-	-
Deep overbite				
Exist	0.02	0.017	0.089	0.260
Non-exist	Reference	-	-	-
Deep overjet				
Exist	−0.011	0.013	−0.07	0.393
Non-exist	Reference	-	-	-
Crossbite				
Exist	0.003	0.029	0.01	0.919
Non-exist	Reference	-	-	-
Openbite				
Exist	0.026	0.023	0.084	0.270
Non-exist	Reference	-	-	-
Maxillary crowding				
Exist	0.003	0.013	0.016	0.837
Non-exist	Reference	-	-	-
Mandibular crowding				
Exist	0.018	0.012	0.107	0.122
Non-exist	Reference	-	-	-

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

was shown to be a risk factor for OIRR in maxillary central and lateral incisors. Compatible with our findings, Motokawa et al. [37] and Harris et al. [38] also observed correlations between the severity of root resorption and open bite. Possible explanations were the long-term orthopedic forces of tongue thrusting or hypofuncional periodontium accompanying anterior open bite that resulted in the enhancement of root resorption rate. The promoting effect of deep overbite on root resorption in maxillary first molars revealed in our results might also stem from this. Like researches conducted by Linkous et al. [7], Marques et al. [36], Kaya et al. [11] and de Freitas et al. [39] other malocclusion factors such as skeletal pattern, overjet and under bite involved in our study were not significant predictors of OIRR.

The regression equations reported in this study explained at an average of 10 percent of the variance in OIRR, where nearly 5 percent was explained by age. In contrast, the impact of in-treatment variables on outcomes is clearly greater than these patient-related factors [19]. However, as mentioned earlier, such treatment-related factors cannot be used as predictors to help clinicians estimate OIRR from the outset [40]. Findings of our study implied that the detection of OIRR through 3D CBCT data had relatively high sensitivity and the risk of OIRR can be predicted to a certain extent through particular patient-depended factors before orthodontic treatment.

However, there are several limitations in this study. Firstly, this is a retrospective study that includes patients treated by the same orthodontist over a certain period of time. While this ensures consistency in the treatment methods, it may introduce selection bias, limiting the ability to draw causal inferences between patient-related factors and orthodontically induced root resorption (OIRR). Additionally, although data were collected from

Table 14 Regression equation for root resorption rate prediction

Tooth position	Regression equation	R^2
Maxillary		
Central incisor	Y = 0.049 + 0.046 (Adult) + 0.024 (Female) + 0.026 (Openbite)	0.139
Lateral incisor	Y = 0.057 + 0.04 (Adult) + 0.012 (Female) + 0.046 (Openbite)	0.11
Canine	Y = −0.007 + 0.073 (Adult) + 0.01 (Female)	0.154
Premolar	Y = 0.003 + 0.063 (Adult)—0.036 (Maxillary crowding)—0.034 (Mandibular crowding)	0.151
Molar	Y = 0.073 + 0.013 (Deep overbite)—0.024 (Maxillary crowding)	0.049
Mandibular		
Central incisor	Y = 0.03 + 0.045 (Adult)	0.03
Lateral incisor	y = 0.038 + 0.054 (Adult)	0.056
Canine	Y = 0.002 + 0.051 (Adult) + 0.017 (Female)	0.109
Premolar	Y = −0.011 + 0.062 (Adult) −0.014 (Mandibular crowding)	0.113
Molar	Y = 0.028 + 0.33 (Adult)	0.042

108 patients, the sample was somewhat imbalanced due to the low proportion of patients with conditions such as open bite, crossbite, and severe deep overbite. Furthermore, most of the patients came from the same region and ethnic background, which may limit the generalizability of the results to broader populations. Therefore, future studies may need to collect patient samples from multiple centers with diverse backgrounds, increasing the sample size while ensuring richness in relevant factors, thereby enhancing the applicability and generalizability of the findings. Finally, the study used linear regression for analysis, assuming a linear relationship between variables. However, the relationship between OIRR and patient-related factors may be nonlinear. Thus, future research may require more complex modeling methods to better capture these relationships.

Conclusions

In this study, we presented a time-efficient, accurate and reliable method to obtain root volume data from CBCT images by applying a deep learning based model for tooth segmentation. Results demonstrated that:

Compared to before orthodontic treatment, the average volume reduction after orthodontic treatment had a statistical significance.

Orthodontic treatment did not affect normal root development of permanent teeth.

Underage patients were more likely to achieve less root volume loss rate after orthodontic treatment compared with adult patients.

Existence of moderate to severe crowding resulted in less root resorption in maxillary premolars, molars and mandibular premolars.

Greater root resorption occurred in maxillary central and lateral incisors from patients with anterior open bite and maxillary first molar from patients with deep overbite.

Skeletal pattern, overjet and underbite did not influence the root volume loss rate after orthodontic treatment.

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Authors' contributions
Qianhan Zheng and Jiaqi Lin contributed equally as primary authors, and Ting Kang, Weifang Zhang and Xuepeng Chen contributed as corresponding authors. Conceptualization, Qianhan Zheng, Jiaqi Lin, Yongjia Wu and Mengzi Zhou; Methodology, Qianhan Zheng, Jiaqi Lin and Yongjia Wu; Data Curation: QIanhan Zheng, Jiaqi Lin, Jiahao Chen and Xiaozhe Wang; Validation, Qianhan Zheng, Jiaqi Lin, Mengzi Zhou, Jiahao Chen and Xiaozhe Wang; Writing—Original Draft, Qianhan Zheng and Jiaqi Lin; Writing—Review & Editing, Ting Kang, Weifang Zhang and Xueoeng Chen; Supervision: Ting Kang, Weifang Zhang and Xuepeng Chen. All the authors have read and agreed to the published version of this manuscript.

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Data availability
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Ethics approval and consent to participate
The study was retrospective in design and was reviewed and approved by the Ethics Committee of the Affiliated Hospital of Stomatology, School of Stomatology, Zhejiang University School of Medicine (2024–001[R]). All images were essential for model training and clinical validation, ensuring that patient-specific information was anonymized in compliance with ethical standards. This study was conducted in accordance with the principles of the Declaration of Helsinki. Informed consent was obtained from all participants for the use of data.

Consent for publication
No information that could lead to the identifcation of the study participants is included in the manuscript. Consent for publication is not applicable.

Competing interests
The authors declare no competing interests.

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